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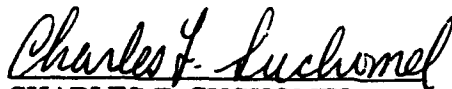
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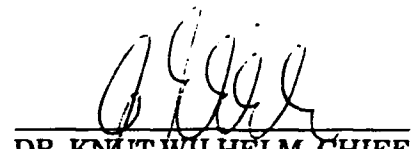
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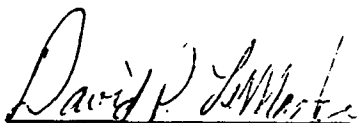


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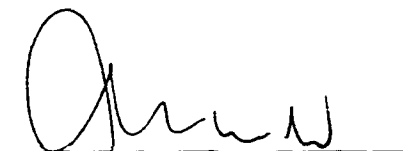
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13. ABSTRACT (Maximum 200 words) The report summarizes the research work into aircraft flight control concepts carried out by WL and DLR under the MoU. Addressed are the methods and scientific approaches used for two subtasks as "Pilot vehicle integration" and "In-Flight Simulation Methodologies". Main emphasis from WL is laid on the different projects performed on the NT-33 and TIFS In-Flight Simulators in order to identify the influence of various system related parameters on longitudinal and lateral handling qualities. The work done by DLR describes the specific technique to be used for ground attack tasks (GRATE) for handling quality research and the development and system identification of DLR's new In Flight Simulator ATTAS.		

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SUMMARY OF A JOINT PROGRAM OF RESEARCH INTO AIRCRAFT FLIGHT CONTROL CONCEPTS

1. BACKGROUND

The US Air Force Wright Laboratory's Flight Dynamics Directorate (WL/FI) and the German Deutsche Forschungsanstalt für Luft- und Raumfahrt's (DLR's) Institut für Flugmechanik are both conducting flight control and flying qualities research. A Memorandum of Understanding (MOU), titled "Aircraft Flight Control Concepts," is continuing to facilitate coordination of related portions of the two individual programs. It has been used to plan and conduct both complementary and joint programs, profiting from each other's work and minimizing duplication.

The technical programs in the two countries are described in Annex B to the MOU. The Project Officer for Germany during the period of this report was Dr. Knut Wilhelm. The Project Officer for the United States was Mr. Robert W. Woodcock until March 1989. He was succeeded by Mr. Brian W. Van Vliet.

In accordance with Annex A to the MOU, the activities in the US and Germany were coordinated through joint review and planning meetings of the Project Officers and their technical teams. The primary purpose of these meetings was of technical interchanges and for reporting on the status of the various studies being pursued in both countries.

2. INTRODUCTION

As outlined in the previous summary report of our joint activities (AFWAL-TR-83-3057/DFVLR-IB 111-83/21), aircraft flight control systems continue to be used more and more to augment or modify airframe characteristics to improve flying qualities or reduce pilot workload. Missions become more complex, involving more numerous and more complex subsystems and interactions, while threats become more menacing. Optimizing flying qualities is an effective way to allow the pilot to concentrate on other necessary tasks. While some flight control functions will be automated, the pilot must remain in charge, capable of both controlling his aircraft and taking a more active role in the event of a subsystem failure. Although flight control reliability is improving, failure consequences can be more serious.

Air combat and ground attack tactics are changing, with more emphasis on agility as flight control and fire control advances enhance the effectiveness of off-boresight shots, etc. Transport, cargo and bomber aircraft missions also are becoming more demanding, with low-altitude penetrations and aerial delivery, short-field operation, etc. Expanded flight regimes involve additional flying qualities concerns. Different aspects of flying qualities appear in various segments of these advanced missions, highlighting a number of flight control and flying qualities factors which must be addressed. At the same time, increasingly complex aircraft systems and control system enhancements make necessary and possible a more comprehensive, integrated design approach for a multi-input, multi-output flight control system which interacts with structural, propulsion, guidance, etc. systems but still considers the pilot adequately.

In the end, all advances must be verified and quantified. To an extent, this may be done through simulation and test on the ground. Still, evaluation in flight remains the ultimate test. For a number of applications, flight testing is the only adequate means of assessing the result. Because each aircraft design furnishes only a data point after the fact, both DLR and WL are constructing new in-flight simulators with which to evaluate a broad spectrum of advanced aircraft systems and characteristics over representative flight envelopes. Variation of flying qualities over a wide range is a most important aspect of these in-flight simulators. Cooperation in the development of these unique aircraft is the subject of Task II of this MOU.

2.1 DLR RESEARCH RELATED TO THE MOU

a. Task I: Pilot-Vehicle System Integration

The objective of DLR's handling qualities research program is to investigate task-oriented handling qualities, especially for precision tracking tasks like approach and landing, and ground attack. The goal is to develop the technology data base, through theoretical and experimental studies, upon which handling qualities criteria for advanced control concepts and new missions should be established.

For the analysis of the pilot-vehicle system behaviour, effective test methods are necessary that yield reliable results and identify pilot-vehicle system integration problems.

DLR's activities of Task I, therefore, have been concentrated on the development of a valuable flight test method for flying qualities investigation for precision tracking tasks. In addition, methods for the determination of flying qualities parameters with respect to existing and newly proposed criteria have been developed and were applied to test data.

Main points of the activities were

- (1) Development of the Ground Attack Flight Test Technique (GRATE),
- (2) Preparation and Conduct of joint US/FRG simulator and flight tests utilizing the GRATE technique,
- (3) Development of Interactive Flying Qualities Program Packages (DIVA, FMLIB) and application to flight test data.

b. Task II: In-Flight Simulation Methodologies

DLR has developed the in-flight simulator ATTAS (Advanced Technologies Testing Aircraft System) which is based on the short haul passenger transport aircraft VFW 614.

The aircraft will mainly be used for evaluating new flight control concepts, performing handling qualities research and test pilot training.

The equipment for in-flight simulation comprises a left side evaluation cockpit with 2-axis sidestick, two variable Head Down Displays (HDD), duplex-simulation computer configuration and fly-by-wire control for primary flight controls, both engines, landing flaps and direct lift control flaps.

In the process of the development of in-flight simulation techniques the work of Task II plays an essential role. This includes the controller design, the software implementation and validation as well as the application of system identification methods which is the only way to achieve precise mathematical models necessary for model-following controller optimization.

2.2 WL RESEARCH RELATED TO THE MOU

a. Task I: Pilot-Vehicle System Integration

WL's flight control research develops design concepts, criteria and methods useful for future aircraft systems and for improving current aircraft. Flying qualities work is directed at development and validation of criteria to incorporate in the military standard and handbook MIL-STD-1797, "Flying Qualities of Piloted Aircraft." Much of the effort during this period involved preparation, editing and coordination of that voluminous document, with input from many sources including Germany under this MOU.

Approach and landing continues to be an area of concern, for both conventional and STOL operation. While handling criteria seem fairly well in hand for powered-lift STOL aircraft, landing on bomb-damaged runways presents a challenge particularly to fighter aircraft. FDL has conducted analyses and simulations leading to development of flying qualities requirements and design of the WL F-15 STOL/Maneuver Technology Demonstrator (S/MTD) aircraft.

While current flying qualities criteria treat static and linear dynamic characteristics, increased emphasis on agility has highlighted the need to consider the nonlinear behaviour in large-amplitude maneuvers. FDL has made several preliminary attacks on this problem.

As combat flying becomes more demanding of the pilot, we need to orient flying qualities requirements toward more specific tasks and to provide flight control system design techniques that facilitate proper consideration of flying qualities. Both normal and failure states are of concern. With increased use of displays, WL/FI has found it necessary to look into their dynamics.

Both subtasks of the MOU's Task I, piloted-vehicle analysis and handling quality correlations, play an essential role in this research.

b. Task II: In-Flight Simulation Methodologies

The NT-33A Variable Stability Airplane has variable pitch, roll, yaw, and thrust control, a variable head-up display (HUD), center or sidestick, and variable feel. WL's other in-flight simulator is the NC-131 TIFS (Total In-Flight Simulator), which has a two-place evaluation cockpit in an interchangeable nose; vertical fins on the wings can generate side force, and fast-acting wing flaps can generate direct lift. Both aircraft are kept busy training test pilots, evaluating new aircraft designs, performing research evaluations, etc.

VISTA, The Variable In-flight Stability Test Aircraft, is a two-place F-16D airplane, now in development at General Dynamics in Fort Worth, Texas as a US Air Force-Navy project, managed by WL. Calspan Corp. is concurrently designing and installing the simulation equipment. This airplane will replace the aging NT-33, but with much more systems simulation capability as well as a flight envelope representative of contemporary fighters.

3. APPROACHES AND METHODS

3.1. DLR

a. Task I: Pilot-Vehicle System Integration

DLR's activities in Task I concentrated on developing methods for the determination of flying qualities and on generating a data base for the evaluation of flying qualities criteria.

Analysis and computer simulation as well as ground-based piloted simulation and flight tests have been used in this effort.

Investigation of flying qualities of highly augmented aircraft, including pilot control strategies, require a detailed knowledge of the total pilot-vehicle system behaviour. System identification techniques have proven to be a valuable tool to describe the vehicle dynamic behaviour. Based on the experience in the design and application of system identification techniques, DLR started to extend this technique to flight test methods which allow the detailed analysis of the total pilot-aircraft system.

These investigations resulted in the evaluation of the Ground Attack Flight Test (GRATE) technique, which has been developed to accomplish required closed-loop excitation of the total pilot-aircraft system during actual air-to-ground flight tests. After having tested this technique in a cooperative research program of DLR and the German Federal Armed Forces Engineering Center (WTD 61), GRATE was implemented and applied to low-order dynamic models of a ground attack and a fighter aircraft in the Large Amplitude Multi-Mode Aerospace Research Simulator (LAMARS) at WL as part of a joint DLR/WL simulator program.

In addition, this technique was tested in a joint (DLR, WTD 61, WL, NASA-Dryden, AFFTPS, and CALSPAN) flight test program at Edwards AFB using a T-38 and the NT-33A In-Flight Simulator. In these tests the NASA-Dryden's Adaptable Target Lighting Array System (ATLAS), which is a derivative of the DLR GRATE System, was used.

For the application and correlation of handling qualities criteria, methods for the determination of flying qualities parameters have been developed. In this field, DLR's activities have been concentrated on the development of interactive flying qualities analysis program packages, which include Low Order Equivalent System Approximation (POLYKO) and options for applying directly flying qualities criteria like Neal-Smith, Bandwidth, Roeger, Diederich, Gibson etc.

These methods were taken as the basis for the investigation of the applicability of flying qualities criteria.

b. Task II: In-Flight Simulation Methodologies

The simulation capability and fidelity for ATTAS (Fig. 1) have been improved by developing a multi-processor system which is able to compute in parallel the required functions.

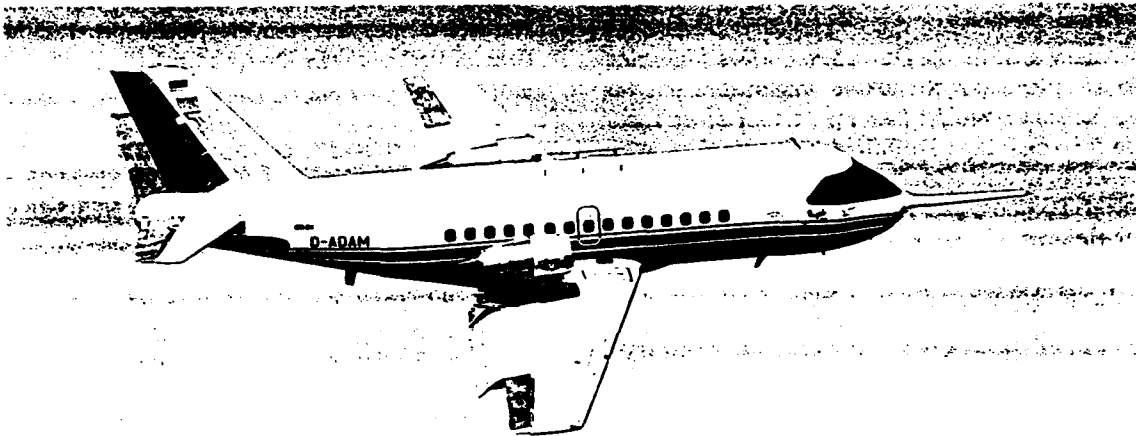


Fig. 1 ATTAS Aircraft

The total system consists of four Rolm MSE 14- and one Hawk 32-computer linked by a high speed fibre optic bus system. The computational cycle time for in-flight simulation application is 25 ms which is far below values which will have an impact on the handling qualities.

Further, special electro-hydraulic actuators have been designed and developed with high bandwidth and low phase shift for the simulation frequency region. In order to develop and validate the simulation software, a ground-based ATTAS-System Simulator has been built which is able to simulate all functions and which is able to represent data identical formats under real-time conditions. Additionally, a fibre optic bus link between the ATTAS-System Simulator and the ATTAS-aircraft allows hardware-in-the-loop testing of the total system. To improve model-following-controller robustness, new techniques for control system optimization have been developed using singular value method.

3.2 WL

a. Task I: Pilot-Vehicle System Integration

WL's work is carried out in several ways: in-house, sponsoring academic projects and theses, and - in the greatest share - through contracts with industry, research organizations, and universities. We try where possible to generalize from our support of advanced development programs.

Development of flying qualities criteria inherently involves both of Task I's subtasks. Pilot-vehicle analyses study both new aspects and observed phenomena, and also are adapted for use as flight control system design tools. Quantitative data, however, are needed both to validate the analytical results and to derive numerical bounds on the parameters selected for use in criteria. Revision of MIL Standard 1797 also involves survey of related work in a number of organizations.

The two approaches to pilot modeling which WL has used are (a) the adaptation of classical servo theory, as developed by McRuer et al., at Systems Technology, Inc. (STI) and (b) Kleinman et al., (from Bolt, Beranek & Newman) Optimal Control Model, which assumes that the pilot tries to act as an optimal controller.

WL simulators employed range from fixed-base cockpits to the LAMARS moving-base cockpit (described in the previous MOU summary report) to the in-flight simulators which are involved in Task II. Data points are also obtained from Advanced Development Programs such as the AFTI-F-16, AFTI-F-111, X-29, and F-15 S/MTD research aircraft.

WL has investigated several analytical techniques to explore nonlinear flying qualities. These techniques are discussed in Section IV. A related approach is to examine combat maneuvers to determine more directly particular characteristic aspects that relate to flying qualities. While certain methods show promise, we have not yet progressed beyond the preliminary stage.

While many advances have been made in flight control systems, the result too often has been a need for redesign or operating restrictions because of poor flying qualities. WL is attempting not only to correlate data, but to develop conceptual and preliminary design methods which aid airframe, flight control, and related system designers to get good flying qualities.

b. Task II: In-Flight Simulation Methodologies

Simulation capabilities of the NT-33 and 11FS airplanes have been enhanced by a number of modifications.

1. TIFS Improvements

The most significant improvement in TIFS capabilities has been the development of the Avionics Systems Test and Training Aircraft (ASTTA) configuration (Fig. 2). This is a highly instrumented flying test bed for testing of tactical sensors and other avionics systems. It is a unique tool to train system designers and testers in in-flight test techniques on these systems. ASTTA incorporates air-to-air and air-to-ground radar and inertial navigation systems as well as infrared and electro-optical detection systems as found in various tactical aircraft. These systems can be operated as stand-alone or in an integrated fashion.

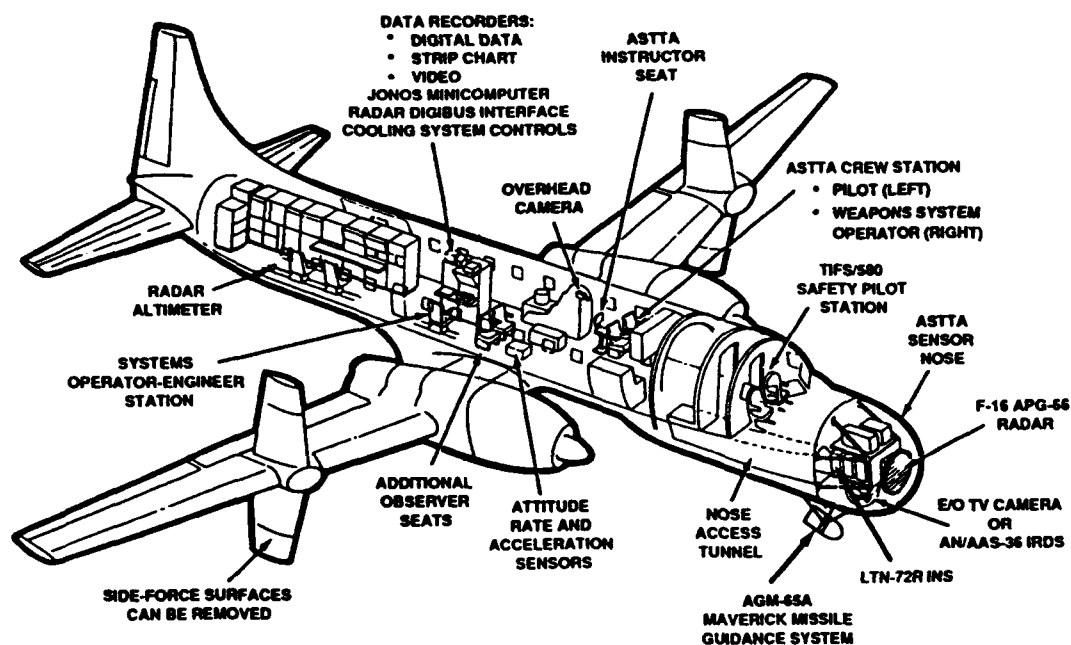


Fig. 2 TIFS in ASTTA Configuration

In the ASTTA configuration the evaluation cockpit nose is replaced by a radar-transparent avionics nose housing an F-16 APG-66 radar and an AN/AAS-26 FLIR. An operator/training crew station is also added in the main cabin. The crew station is configured for side-by-side pilot and weapon systems operator controllers and displays, including a hydraulic variable-feel sidestick and a video system. It provides hands-on experience in a real-world environment. The aircraft can be flown by the pilot from this station using the TIFS fly-by-wire system. Another subsystem incorporated to support the ASTTA configuration was a freon cooling system for the radar, computers, and crew.

Since development of the original ASTTA configuration in 1984/85, a number of additional avionics systems have been incorporated, including a Global Positioning System (GPS) in 1988, a long-range navigation (LORAN) system in 1990, and the nose section of a Maverick electro-optical guided missile mounted under the ASTTA nose in 1990.

Another significant improvement in TIFS simulation capabilities was a computer upgrade carried out in 1986/87. The old Sperry Univac RV77-400 Varian fixed-point digital computers were replaced with state-of-the-art Rolm Hawk 32 floating-point digital computers. The Varian computers were an increasing source of lost flights and excessive ground check-out time. The new computers were faster, had more memory, and could handle much more complex models than the older computers.

The data acquisition and processing system was also improved. The existing system became obsolete during the early 1980s. It was replaced by a system based on the Ampex AR-700 airborne data recorder which is commonly used in the flight test community. The ground playback system was replaced by a new "Quick Look" system for quickly getting time history hard copy after a flight and by a computer system for processing and analyzing flight data.

The elevator actuation system was tested and studied using a computer model to investigate various ideas to increase bandwidth. Much knowledge was gained but the conclusion was reached that, although some ideas were partially successful, roughly half of the time delay in pitching motion control is due to fuselage bending, and, therefore, cannot be shortened by any change to the elevator control system or structure.

A similar study on the direct lift flap system addressed excessive phase lag due to viscous damping created by the bypassed actuator of the dual freedom arrangement. Negative feed-back around the actuator helped on paper and it remains to demonstrate this with the actual hardware.

The TIFS system is limited at high direct lift flap and elevator rates in attempting to alleviate real gusts or to simulate gusts. Part of the limitation is hydraulic shock when a high rate is abruptly arrested. Properly placed accumulators should ease the shock. Investigation of the actual airplane line routings to the direct lift flap revealed a "tee" intersection where one or two accumulators could possibly improve matters.

Four display additions were made. Three in the safety cockpit provide better situation awareness. The direct lift and side force surface position indications are now repeated on top of the glare shield in a head-up position. The entire copilot's panel has been upgraded and, in the extra space created, a monitor of the ASTTA radar display has been added. The fourth display addition is a multifunction electronic display currently mounted in the evaluation cockpit.

There were also other miscellaneous improvements. The TACAN and the inertial platform signals were made available to the digital computing system. A weight reduction program resulted in relocation of the inverter, a hydraulic filter upgrade, and removal of the UHF DF antenna. The three items totaled about 170 pounds saved. Wing strobes were fitted to improve airplane visibility for safer operation at all times, but particularly at the test ranges.

2. NT-33 Improvements

Many improvements were incorporated in the NT-33 data acquisition and processing systems. The existing data acquisition and processing systems were obsolete and no longer compatible with modern data processing systems. These systems were replaced by an Ampex AR-700 flight data recorder, a new control header for the data recorder, and a "Quick Look" flight data storage and ground playback system. This system allowed more compact storage of data as well as immediate access to data following each flight. In addition, a video camera recording system was installed in place of the old film camera. Advantages of the VCR system over the film camera included a wider field of view, more reliable operation, longer operating time per cartridge (60 - 90 minutes versus 3 minutes), synchronized audio and video recording, and immediate availability after the flight. (The old film cartridges had to be sent to film processing before they could be viewed.)

Improvements were also made to the NT-33 gust response compensation. A complementary filter technique was implemented that blends the angle of attack and sideslip vane signals with their respective inertially derived rate signals to obtain a and b signals insensitive to turbulence. The resultant signals, accurate in phase and amplitude throughout the frequency range of the airplane, are now used in the variable-stability system (VSS) feedback loops. A secondary output of the filters is an accurate estimation of the vertical and lateral components of the ambient turbulence. With the complementary filters installed in the aircraft, the α , $\dot{\alpha}$, β , and $\dot{\beta}$ gains to the control system are not limited by the vane measurement response to turbulence, and there is a significant improvement to the gust response compensation.

A major upgrade to the NT-33 programmable display system was carried out. The most significant display improvement was replacement of the obsolete Programmable Display Generator (PDG) with an F-18 Multifunction Display Indicator (MDI). The old processor was unreliable and becoming increasingly difficult to maintain. The new processor is more reliable, more maintainable, and more easily programmed than the old PDG. A rear-seat cockpit monitor was provided which allows the safety pilot to observe the HUD symbology and forward external view. An improved C-12 compass replaced the old J-2 compass system. Likewise a more modern attitude indicator was installed in the rear cockpit in place of the J-8 ADI. A TACAN was given to the NT-33 program by Foster Air Data, Inc. and it replaced the existing DME. A digital readout of distance and ground speed is now available and a previously inoperable needle on the RMI now points to the TACAN station. In conjunction with the TACAN and ADI installation the rear cockpit instruments were rearranged to provide a better instrument scan. The old left windscreen quarter panel was discolored and an improvement project funded replacement of this panel. Another airframe improvement was the replacement of the old ignition system with a newer solid state system.

VSS improvements included six more D/A converters added to the Rolm digital computer. This brought the total D/As up to 12. New 15V DC and 28V DC power supplies were added to the VSS to eliminate many unreliable voltage regulators.

Being incorporated in VISTA are special instrumentation, a strong landing gear, faster flight control actuators, a variable stability flight control system, evaluation cockpit, and safety-pilot cockpit features, computers, etc. First flight took place early in 1992. As on DLR's ATTAS, Rolm Hawk computers are used. Fig. 3 shows the concept (funding does not permit variable side-force capability at this time).

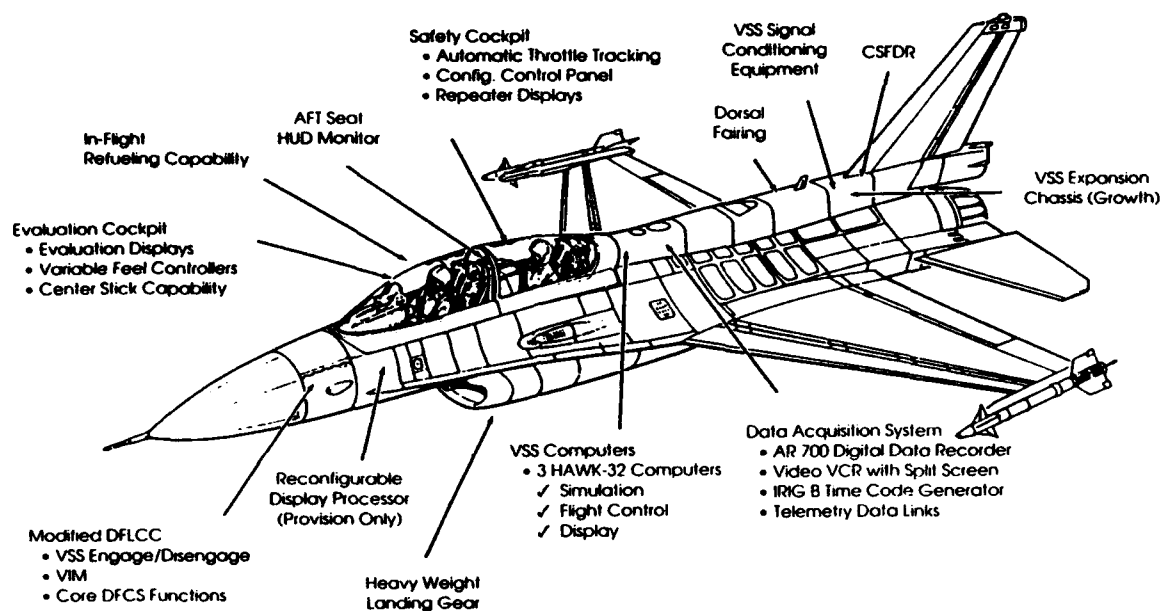


Fig. 3 VISTA Concept

4. RESULTS FROM CURRENT US WORK

4.1 Task I

A new set of flying qualities for fixed-wing military aircraft, MIL-STD-1797, was issued. The standard and handbook, based on a draft by STI's Roger Hoh et al., AFWAL-TR-82-3081, was modified as a result of in-house work and extensive review throughout the flying qualities community in the US and western Europe. The handbook, appended to the standard, gives rationale, guidance, and lessons learned for the requirement and the required verification. For each requirement, guidance includes recommendation for tailoring to a particular case, derivations, and data bases, and guides to critical flight conditions. The standard and handbook have been furnished to the German Government and DLR under the terms of our MOU. A triservice (AF, Navy, Army) version was published in 1990 as MIL-STD-1797A.

WL sponsored Air Force Institute of Technology (AFIT) and Purdue University theses on pilot-vehicle analysis of landing approach and flare. Using an autoregressive time-series identification routine (Biezd and Schmidt, 1984 AIAA Guidance and Control Conference). DiDomenico found pilot ratings to improve with increasing separation of the pilot-closed-loop crossover frequencies for pitch control and for flight-path control (Fig. 4). Anderson used the Kleinman Optimal Control Model (OCM) in an equivalent single control loop encompassing both pitch and flight-path control. With that approach he correlated pilot ratings with the closed-loop bandwidth achieved (Fig. 5), peak amplification and pilot phase compensation (Fig. 6), and the low-frequency open-loop peak (Fig. 7).

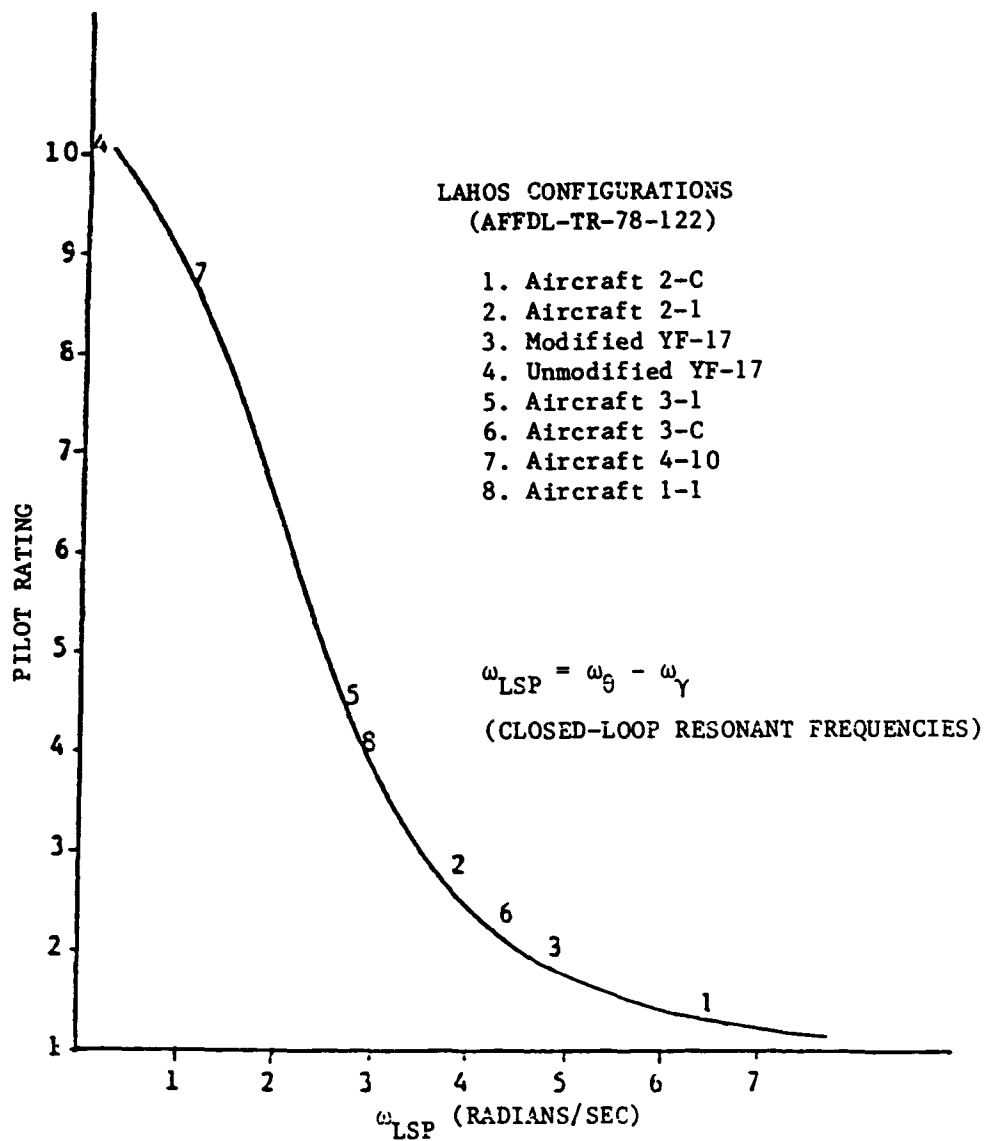


Fig. 4 Loop Separation Parameter

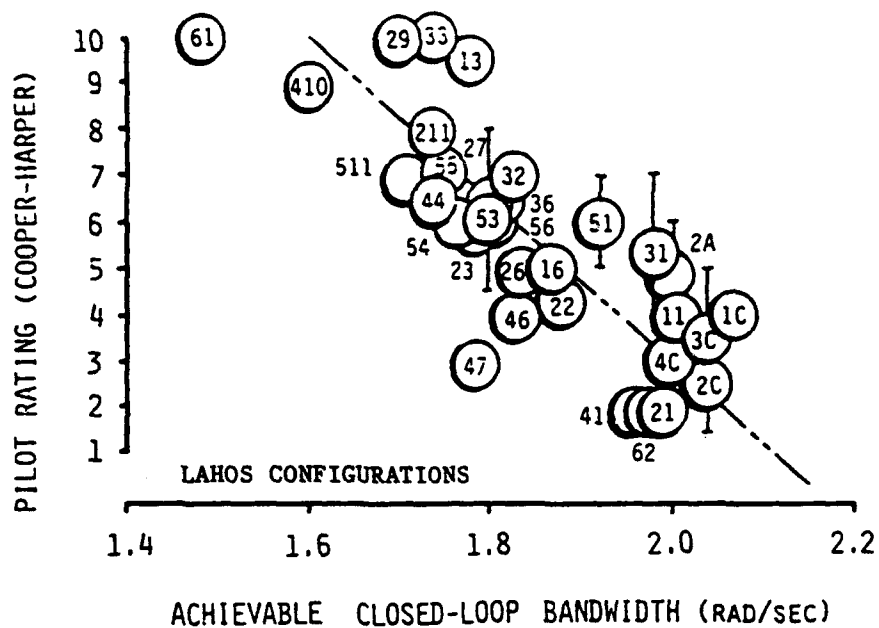


Fig. 5 Pilot Rating and Bandwidth Correlation

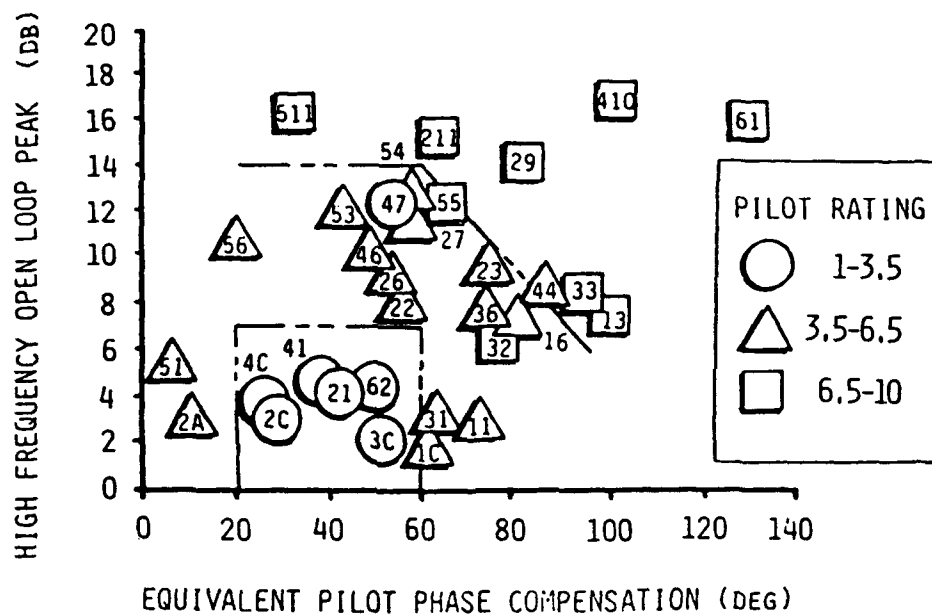


Fig. 6 High Frequency Open-Loop Peak Results for the Flight Path Tracking Task

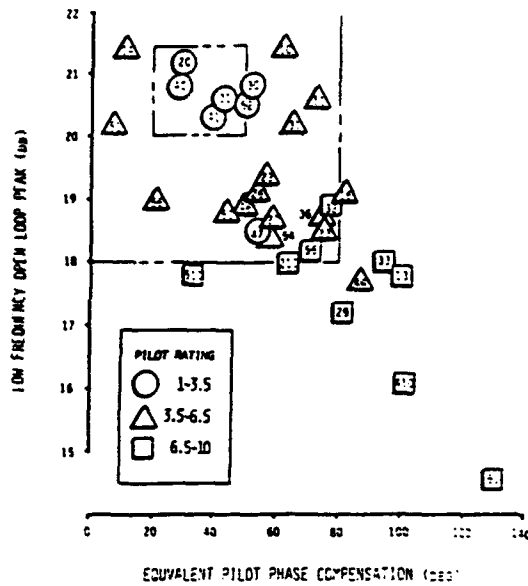


Fig. 7 Low Frequency Open-Loop Peak Results for the Flight Path Tracking Task

Systems Technology, Inc. (STI) has developed a pilot model for divided attention, using the crossover model (pilot's describing function adjusted to give an open-loop frequency response approximating k/s around the crossover frequency), which can be used to study multiple flying qualities degradations. Analysis is done on microcomputer. This technique, and also a conjectured product rule, the multiaxis rating R_m for m axes

$$R_m = 10 + \frac{-1(m+1)}{8.3(m-1)} \frac{m}{\prod (R_i - 10)}$$

are being studied to determine the effects on pilot rating of multiple handling qualities degradations. A piloted simulation in the WL LAMARS simulator was conducted in 1988. The results of this simulation were published in WRDC-TR-89-3125. D.T. McRuer's "Pilot Modeling" in AGARD-LS-157, Advances in Flying Qualities, outlines his theory. Divided attention decreases the permissible crossover gain and increases the pilot remnant (Fig. 8).

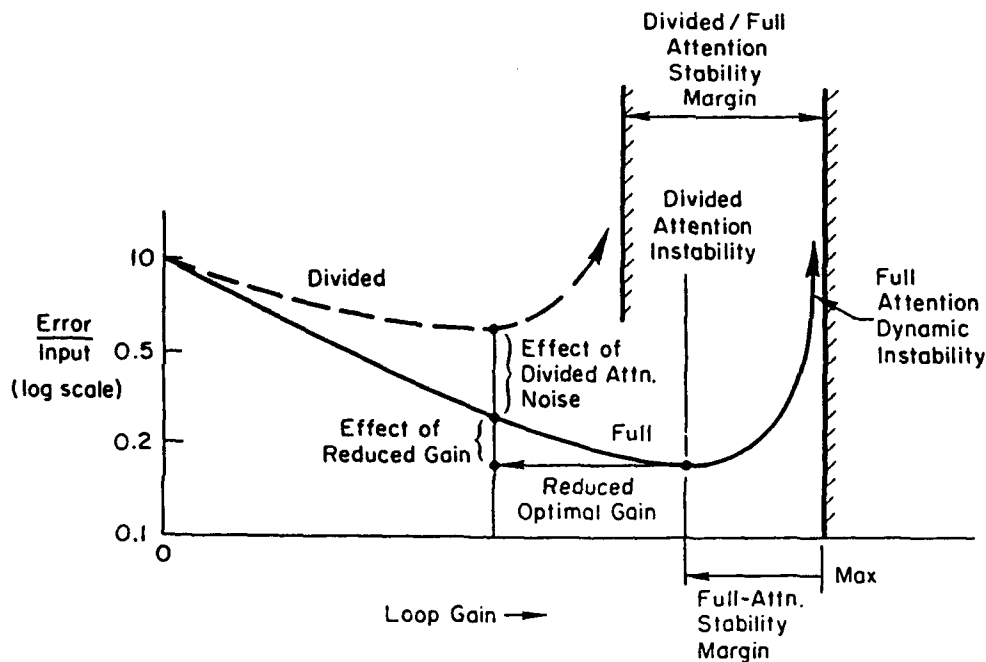


Fig. 8 Consequences of Divided Attention

Honeywell has also used the OCM, with (a) Schmidt's cooperative synthesis of optimal flying qualities and flight control design and (b) Doyle and Stein's structured singular value technique, to synthesize optimal display dynamics (Fig. 9). Their results, while preliminary, indicate the possibility of designing display dynamics that meet performance criteria and are robust with respect to pilot-closed-loop stability.

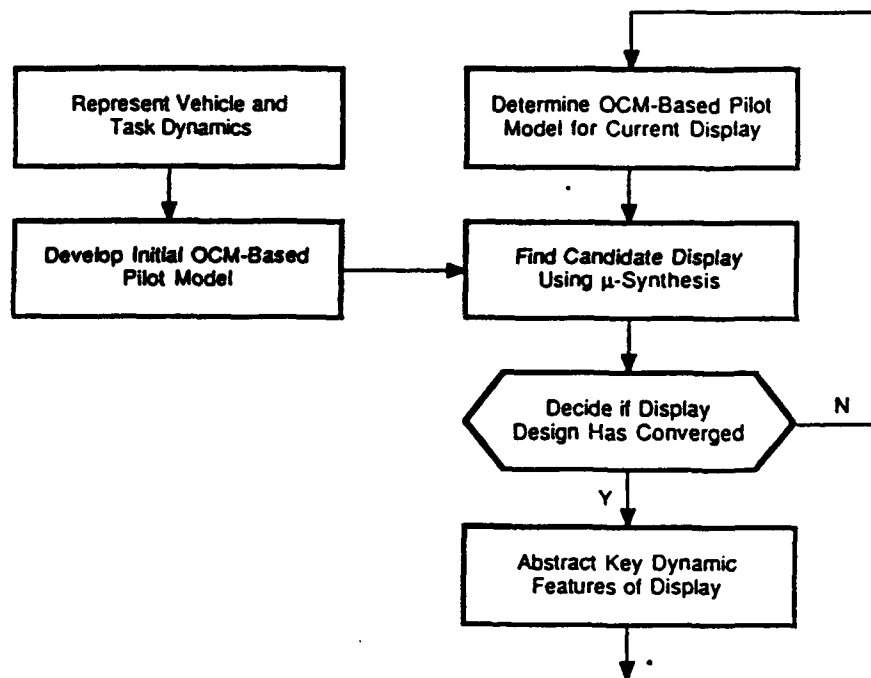


Fig. 9 An SSV-Based Approach for Deciding Display Dynamics

McCormack et al., have investigated the effects of display dynamics in a fixed-base simulation of a simple pursuit tracking task in pitch, with nine pilots. Tracking performance deteriorated markedly as display damping was reduced from 0.707 to 0.2, and significantly as display time delay was increased from 0.0131 to 0.15 to 0.3 sec at either damping ratio (Figs. 10, 11). The deterioration with lower damping was much less pronounced at high (6 r/s) bandwidth, which seemed beyond the range of pilot control. With increasing time delay, pilots rated workload as worse. Aggressive fighter and smoother cargo piloting styles yielded the same rms error. It is planned to continue this work.

Pujara derived a frequency-domain approach to preliminary design of augmentation to meet flying qualities requirements. The resulting program was demonstrated by designing pitch controllers for unstable aircraft, using the short-period requirements of MIL-F-8785C. Pitch rate and normal acceleration were the feedbacks used to obtain the desired short-period frequency and damping. The need is seen to extend flying qualities to STOL aircraft of two types: powered-lift and fighters. While we have considerable experience with powered lift (e.g., YC-14, YC-15, QSRA), the problems of fighter aircraft are somewhat different.

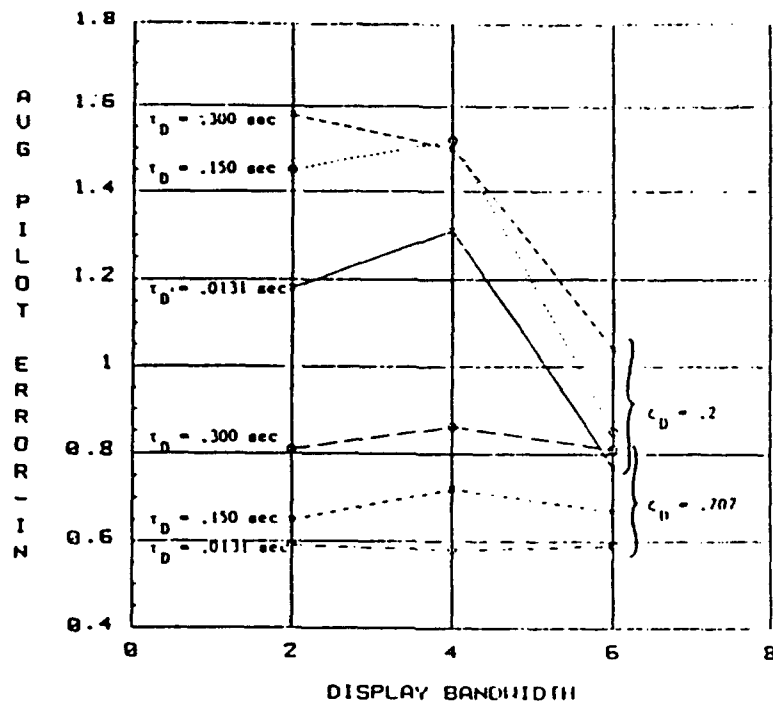


Fig. 10 Aircraft 1 Average Pilot Error vs. Bandwidth

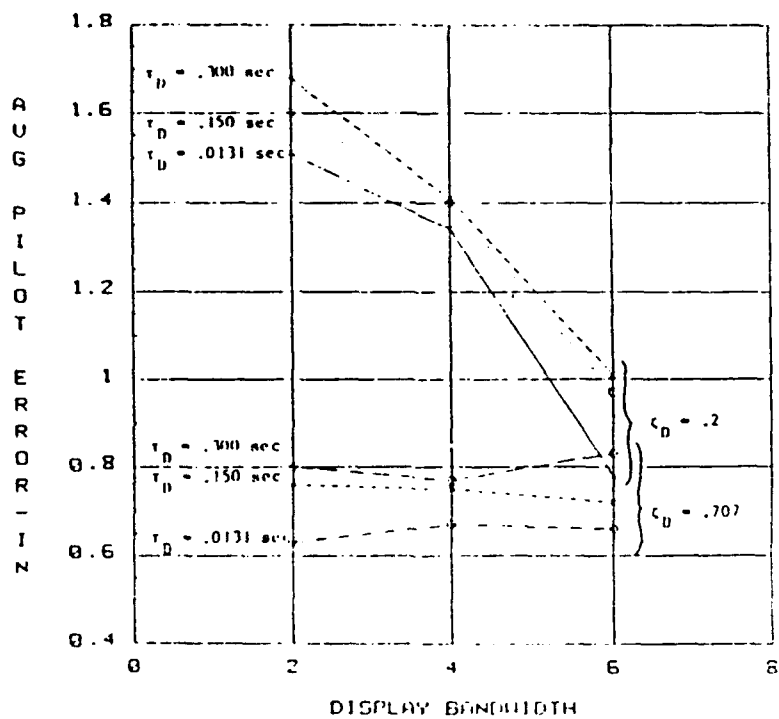


Fig. 11 Aircraft 2 Average Pilot Error vs. Bandwidth

A study examined the flying qualities of STOL aircraft, and a simulator evaluation extended the data base for the fighter type (Figs. 12, 13, 14). An attitude command, attitude hold response type was found most desirable for precise STOL landings but, with sufficiently high bandwidth, the conventional response type was found acceptable.

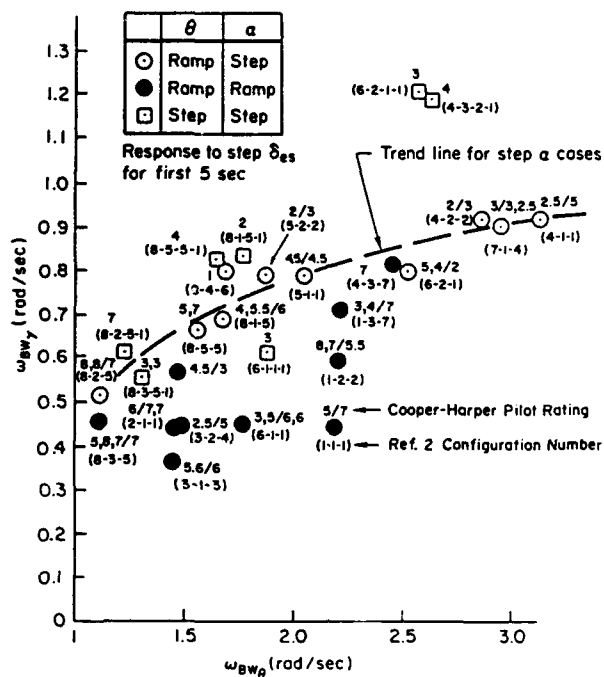


Fig. 12 Pilot Rating Correlations with $(1/T_{\theta 2})_{eff}$ and $\omega_{BW\theta}$
Flared Landing Experiment

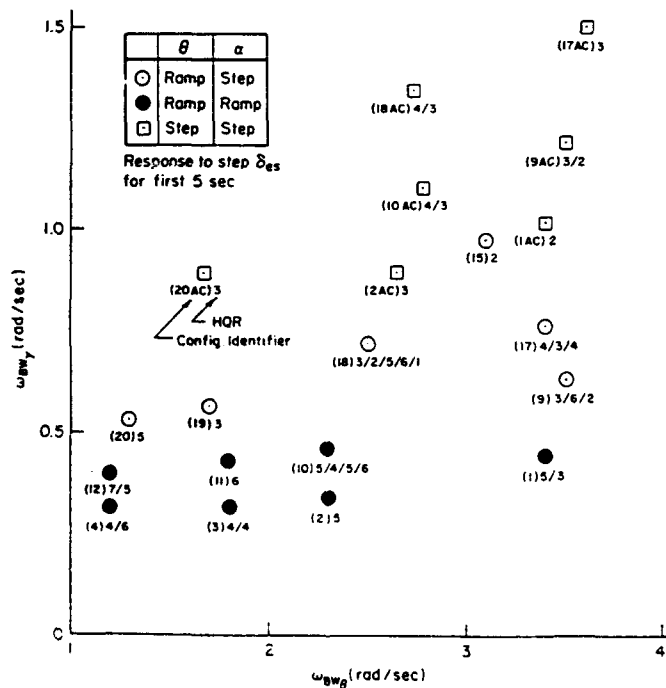


Fig. 13 Fighter STOL Simulation Data (LAMARS)

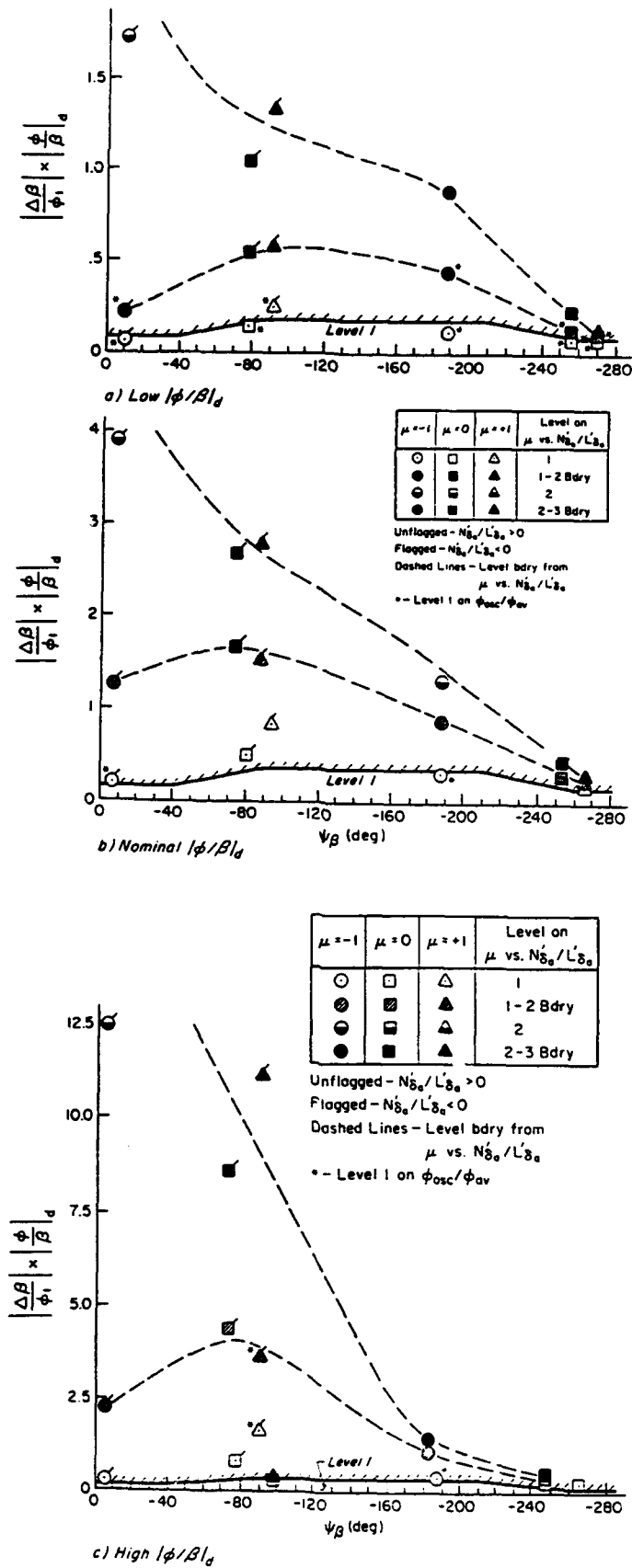


Fig. 14 Sideslip Excursion Characteristics of Turn Coordination Cases

Pilot opinion to correlated with the augmented aircraft path-control (γ/δ) and pitch-control (Θ/δ) bandwidths, corresponding to pilot parallel path and pitch control strategy (bandwidth here, as in MIL-STD-1797, is defined as the highest frequency at which both a phase margin of 45 deg and a gain margin of 6 dB exist). "A wide separation in frequency allows the pilot to spend most of his time on attitude with occasional corrections in flight path resulting in an effectively simultaneous closure. If the bandwidth of the flight path loop approaches that of the attitude loop, the pilot will have a difficult time simultaneously closing both loops ..." A desirable path bandwidth of 1 to 1.5 sec is suggested.

Conventionally, the flight-path response follows the pitch response to pilot commands with a lag, $\gamma(s)/\Theta(s) = 1/(T_{\Theta}2s + 1)$. For a pitch rate command/attitude hold system, however, this relationship holds only if the integrator zero, $1/T_q$, is close to $1/T_{\Theta}2$. Much larger values of $1/T_q$, which have been used to speed the pitch response, cause the flight path to change more slowly than the pitch attitude: $\gamma = \Theta - \alpha$. Then for a step command, with large $1/T_q$ the angle of attack, α , does not resemble a step but ramps off. The pilot's consequent difficulty in judging path response by the pitch response can be troublesome. In the frequency domain, this difficulty corresponds to a region of k/s^2 which may be in the crossover region for flight-path control.

STI's recommended STOL flying qualities requirements also include upper and lower bounds on the effective pitch transfer-function zero. $(1/T_{\Theta}2)_{\text{eff}}$, defined as the frequency at which γ lags Θ by 45 deg. The lower limit corresponds to the MIL-F-8785B's lower limit on n/α for terminal flight phases. "The upper limit ... is based on experience which has shown that the path response bandwidth should be well separated from the pitch response bandwidth ... Evidence to support this is given in the analysis and flight test result obtained by DLR ..." $\text{Log}(\omega_{\text{sp}} T_{\Theta}2)$ is the distance on a logarithmic scale between ω_{sp} and $1/T_{\Theta}2$, and the phase angle between path and attitude at the short-period frequency is

$$\phi(\gamma / \Theta)_{\omega=\omega_{\text{sp}}} = \tan^{-1} \omega_{\text{sp}} T_{\Theta}2.$$

A critical parameter of dynamic as well as static flying qualities is control sensitivity. Analyzing LAHOS (AFFDL-TR-78-122) approach and landing data, for which pilots were free to select the control gain, Sturmer noted a consistent trend of the stick force gradient to increase with increasing short-period frequency (Fig. 15). His further analysis mapped those results and those of AFWAL-TR-81-3116 into the Nichols chart boundaries of Fig. 16. This form of statement in servo analysis terms applies directly to higher-order systems. A later paper puts bounds on a plot of pitch-attitude bandwidth vs. sensitivity at that frequency (Fig. 17), while suggesting a more generally applicable criterion (not a function of $T_{\Theta}2$) in terms of flight-path bandwidth and sensitivity (Fig. 18).



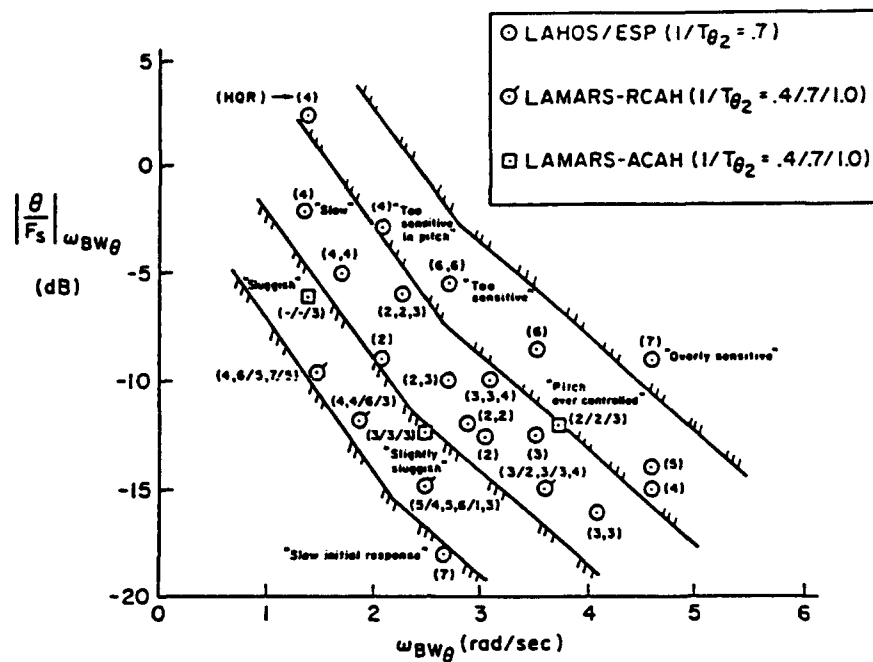


Fig. 17 Pitch Attitude Control Sensitivity Requirements for Centerstick Controllers, θ/F_s Has Units of deg/lb. Configurations Have Equivalent Time Delay, τ_e , Less than 150 ms and $F_s/\delta_e = 5 - 8$ lb/in

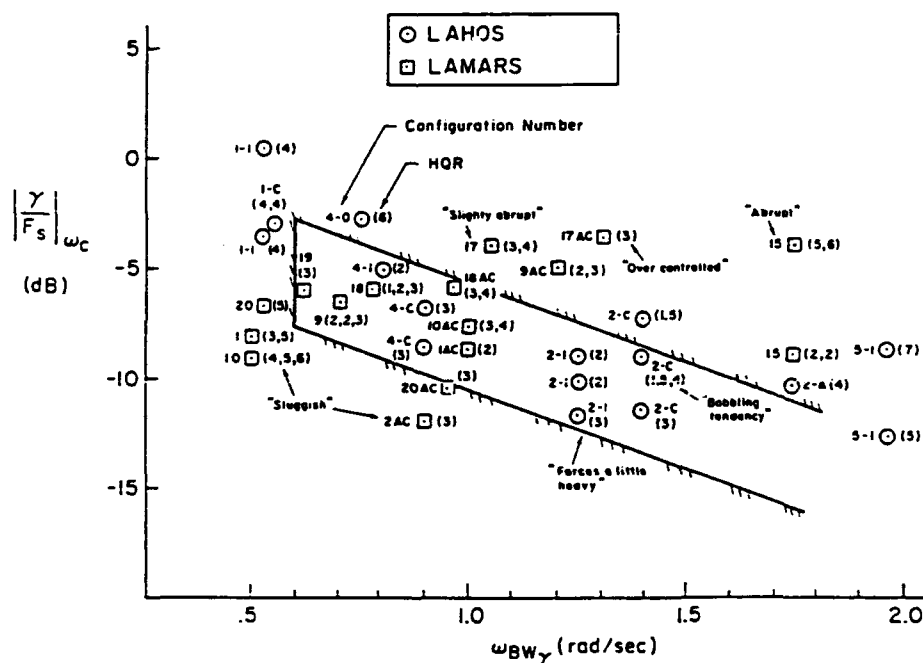


Fig. 18 Desired Flight Path Control Sensitivity at Crossover Frequency (Centerstick Controllers, $F_s/\delta_e = 5 - 8$ lb/in). γ/F_s Has Units of deg/lb; $\omega_c = 1.0$ rad/sec

4. Multi-Degree-of-Freedom Flying Qualities

The flying qualities specification published in 1969, MIL-F-8785B(ASG), for the first time quantitatively defined satisfactory and acceptable ranges of specific modal parameters of an aircraft. This specification was the culmination of approximately 20 years of experimental flight research involving many variable-stability aircraft. For this representative range of aircraft types, the results were sufficiently consistent that it was generally not considered necessary to specify eigenvectors or, because the aircraft were assumed to have conventional geometry and control surface complement, zeros of transfer functions. Three important developments in aircraft flight control technology, however, brought to light the necessity for continued fundamental research in flying qualities requirements. The first development was the appearance of dynamic elements of the control system in addition to the natural dynamics of the vehicle. The second major development was the appearance of the statically unstable airplane configuration which generally required a considerable amount of feedback control to maintain stability and provide for satisfactory and acceptable flying qualities. The third major development involved the use of additional means of producing forces and moments on the aircraft, such as canards, direct lift flaps, and thrust vectoring. It became necessary to interpret these developments in terms of the existing flying qualities specification MIL-F-8785C in order to provide guidelines for the flight control system designer. The purpose of this task was to design, with supporting rationale, a flight experiment on TIFS that would help provide an interpretation of the MIL-F-8785C requirements for the flight control system designer. The experiment involved pitch rate and angle-of-attack command systems and was flight tested on TIFS during the approach, flare, and landing phase of flight.

5. Experimental Investigation of Short Period Response Requirements

An investigation of the short period frequency requirements of MIL-F-8785C was performed using the TIFS. Seven evaluation flights by two test pilots were performed which yielded 35 evaluations of 18 configurations. The experiment examined the minimum frequency boundary at three values of n/α for one true airspeed. The experiment included the effects of pilot location and evaluation task. The data indicated that the current requirement is essentially valid. The minimum acceptable frequency boundary may be reduced, however, when the pilot station is forward of the center of rotation. Also, the phasing between the normal acceleration and pitch rate responses was shown to be a critical determinant of longitudinal short period flying qualities. The results were analyzed using the equivalent systems methodology.

The final report was AFWAL-TR-86-3109, "Experimental Investigation of Short Period Response Requirements of MIL-F-8785C," by R. E. Bailey, December 1985.

6. Chemical Defense Pretreatment Drug Flight Test

The effects of a chemical defense pretreatment drug, pyridostigmine bromide (PB), on in-flight aircrew performance were assessed using the TIFS aircraft. TIFS was used to supply appropriate control feel, handling characteristics, and cockpit instrumentation for a tactical transport simulation. Twenty-one C-130 pilots flew two familiarization and four data flights. During two of the data flights, PB was given to both members of the aircrew using the dosage regime prescribed by the Air Force Surgeon General. The drug was administered using a double-blind technique. All flights simulated a standard tactical transport mission including climb, low-level formation flight, slowdown, drop, escape, and instrument approach. Data were performance in maintaining aircraft parameters, levels of physiological functioning, subjectively rated fatigue and affect, and frequency of critical incidents.

The final report was USAFSAM-TR-87-24, "The Effect of Pyridostigmine Bromide on In-flight Aircrew Performance," by V.J. Gawron, S.G. Schiflett, J.F. Ball, T. Slater, F.R. Parker, M.M. Lloyd, D.J. Travale, and R.J. Spicuzza, July 1988.

7. Flight Test of General Electric Reconfiguration Control System

A flight program was conducted to evaluate General Electric's Reconfigurable Flight Control System and the System Impairment Detection and Classification (SIDC) algorithm. The TIFS aircraft was flown directly as a fly-by-wire aircraft rather than as a simulator of another aircraft. The Flight Control System and the SIDC algorithm were implemented in the two TIFS Varian V77-4400 computers. This flight test program required control redundancy capability. Modifications were incorporated into TIFS to provide this capability by enabling the movement of each direct lift flap, side-force surface, and throttle independently.

Two types of surface failures were considered: partial surface loss and surface lock due to a locked actuator. A failure logic was implemented in the Varian computer to produce the desired failure. The flight control system consisted of a baseline control system and the reconfigurable control mixer. The SIDC system included algorithms for the detection of a locked and partially missing surface. The following surface failures were considered for the evaluation of the reconfigurable control mixer: 1) lock and partial loss of left flap and 2) lock of aileron and rudder. The implementation of SIDC was limited to the detection of an impairment of one of the three surfaces: 1) left flap, 2) right flap, and 3) rudder.

Three specific maneuvers, one for each axis (pitch, roll, and yaw), were designed for the evaluations of the reconfigurable control mixer and SIDC. Reconfiguration in all three axes was achieved successfully with no transients. Pitch reconfiguration did not cause any degradation in pilot rating compared to the baseline control system. Roll and yaw recon-

figuration was achieved with no degradation in pilot rating when the aileron and the rudder were locked close to the trim position. For configurations where the aileron or rudder was locked away from the trim position, pilot rating of the reconfigured system was downgraded compared to the baseline control system. Partial loss and impairment of the left flap were successfully detected by SIDC.

The final report was Calspan Report No. 7205-12, "Flight Test of General Electric's Reconfigurable Control Mixer and the System Impairment Detection and Classification Algorithm," by K.S. Govindaraj, R.F. Gavin, and J.R. Lyons, November 1985.

8. Flared Landing Approach Flying Qualities

An in-flight research program was carried out in the TIFS to investigate longitudinal flying qualities for the flared landing approach phase of flight. The primary emphasis of this in-flight flying qualities experiment was to generate a consistent set of data to find out what the pilot requires to be able to flare and land an airplane. Two separate types of analyses were performed on the data. One was to investigate what kind of commanded response (e.g., angle of attack or pitch rate) and its characteristics that the pilot preferred. The other area was to refine a time history criterion that took into account all the necessary variables and their characteristics that would accurately predict flying qualities. A total of 30.8 hours of evaluation flight time was flown, encompassing 109 separate evaluations with 228 approaches. Seven evaluation pilots took part in this program and represented NASA Langley, NASA Dryden, Boeing, Lockheed, DLR (Braunschweig, Germany), and Calspan. The results of the first part of the program provide guidelines to the flight control system designer in developing systems, using MIL-F-8785C as a guide, that yield the dynamic behavior pilots prefer in flared landings. Results of the second part provide the flying qualities engineer with an accurate predictive tool which indicates how good the resulting system will be.

The final report was Calspan Report No. 7205-13, "A Flared Landing Approach Flying Qualities Study," by N.C. Weingarten, E.G. Rynaski, C.J. Berthe, and S.K. Sarrafian, December 1986.

9. Boeing 7J7 Flying Qualities Assessment

An advanced technology transport, the 7J7, was being developed by the Boeing Commercial Airplane Company. A fly-by-wire digital flight control system and new cockpit controllers were being considered for use in the new transport. As part of this development effort, Calspan assisted Boeing by providing an assessment of the predicted flying qualities and performing in-flight simulation.

Several approaches have been tried to quantify nonlinear flying qualities. The subject is of interest for gross maneuvering in the normal flight envelope and beyond. Herdman at Virginia Polytechnic Institute has applied Volterra series (from integral equations) in an attempt to develop meaningful flying qualities parameters, with examples of a pull-up and wing rock; a detailed report is in AFWAL-TR-88-3040. At Honeywell, Morton et al., have used a dynamic inversion technique, solving separately for the controlled and uncontrolled outputs. They analyzed a roll reversal, a barrel roll, and a diving turn to suggest flying qualities metrics.

STI has surveyed descriptions of combat tactics, maneuvers, performance measures and metrics, and has classified pertinent flying qualities issues as aircraft-centered; tactical, task and maneuver-centered; and pilot-centered perceptual or control. Myers et al., applied differential geometry to describe a helix and a stylized high-speed yo-yo maneuver, and have suggested Riccati equation theory as a way to analyze "escape" phenomena with even-function nonlinearities. At Eidetics, Skow is attempting to correlate a "roll agility parameter," time to bank and stop, with increase in mission effectiveness. All of these techniques show promise of providing some suitable metrics, but the work has been of a preliminary nature.

At the Air Force Test Pilot School (TPS), student projects gathered data on force/deflection characteristics of side-stick controllers, using the Flight Dynamics Directorate's NT-33 Variable Stability Airplane. Other sponsored TPS projects evaluated time delays in the flight control system. The results were analyzed in-house, for use in the requirements of MIL-STD-1797.

With the assistance and participation of DLR and the German Forces Flight Test Center, DLR's GRATE target array (see Section V) was evaluated in WL/FI's LAMARS moving-base simulator. The sequenced-light target array was installed on a terrain board, and a USAF pilot and a German pilot made air-to-ground gunnery runs. Various time delays were added to two baseline fighter/attack aircraft configurations. Increasing time delay incrementally from 0 to 0.3 sec received progressively worse pilot ratings. With the programmed sequence of lights, pilot ratings and performance were insensitive to turbulence intensity (up to a magnitude that precluded tracking), contrary to results with pilot-selected target switching. This unique capability was judged an excellent tool for evaluation of flying qualities in ground attack. Both organizations are evaluating the results. With the small angular separation of the lights, pilots reacted to lateral target offsets with rudder pedal rather than lateral stick commands.

Further, again with DLR's help, the NASA Ames-Dryden Flight Research Facility has adapted the light array for use on an Edwards AFB range. A joint program involving WL/FI, DLR, the same German pilot, NASA, and the TPS evaluated this facility.

4.2. Task II

a. NT-33 Projects

1. Evaluation of the Longitudinal Dynamics of the Vertical Motion Simulator

A project was conducted in 1984/85 to compare the handling qualities of aircraft configurations which are prone to PIOs in both a real aircraft and a ground simulator. The NT-33 was used as the flight test vehicle while the NASA Ames Vertical Motion Simulator (VMS) was programmed as the companion ground simulator. The ground simulator phase of the study, therefore, contained large amplitude motion and a wide field-of-view Computer Generated Imagery (CGI) visual system. The NT-33 provided real-world visual and motion cues during an approach and landing task. The test matrix included five longitudinal aircraft configurations with handling qualities which ranged from good (a rating of 2 on the Cooper-Harper rating scale) to unflyable (Cooper-Harper rating of 10). The variations in flying qualities were produced primarily by adding time delay to an otherwise good aircraft. Pure delays of 100 msec and 144 msec, and an equivalent delay of about 117 msec due to a 12-rad/sec second-order prefilter were added. The unflyable airplane was generated by adding a low frequency fourth-order prefilter and, consequently, a great deal of equivalent time delay, to a reasonably good aircraft. The evaluation task consisted of a visual landing task in which the pilot lined up with the edge of the runway until 100 feet above the ground. He then corrected to line up on the runway centerline and attempted to touchdown at a precise point.

The results indicated that an aircraft configuration with known poor handling qualities will not necessarily be evaluated as such in a ground simulator, even in such a capable simulator as the VMS. The final report was Calspan Report No. 7205-F-5, "Description of NT-33A Configurations for Use in Programming NASA Vertical Motion Simulator (VMS)," by S.A. Buethe, L.H. Knotts, and K.S. Govindaraj, November 1984.

2. In-Flight Simulation of the IAI Lavi Fighter

The NT-33 was used to simulate the Israel Aircraft Industries Lavi new generation fighter during the summers of 1984 and 1985. An in-flight simulation program was prepared to assist in the development of the flight control system and evaluate the Lavi's landing configuration flight characteristics for an air-to-air aircraft, a heavier air-to-ground aircraft, and for a longitudinally stable first flight aircraft known as the B1 configuration. The digital fly-by-wire flight control system was programmed in the NT-33 Rolm digital computer. Two versions of the digital flight control systems were prepared: one with gains optimized for the air-to-air aircraft and the other optimized for the air-to-ground aircraft. An analog back-up flight control system known as the Emergency Back-Up Unit (EBU) was also programmed on the NT-33 digital computer. Gains for all of

these systems could be modified between flights with up to 16 in-flight selectable gain sets for each of eight in-flight selectable flight control programs. In addition, the NT-33 computer generated a HUD which was similar to the one initially planned for the Lavi.

The first simulation session, which was flown during July and August 1984, concentrated on approach and landing handling qualities of the air-to-air, air-to-ground, and first flight (B1) Lavi flight control system configurations. The follow-on session, flown in July and August 1985, continued and refined the previous work, concentrating on the approach and landing handling qualities for the first flight aircraft (B1).

The task reports were Calspan Report No. 7205-F-7, "NT-33A In-Flight Simulation of DIANA Session 1 - Landing/Approach Evaluations," by L.H. Knotts, K.S. Govindaraj, J.R. Easter, and J.E. Priest, September 1984 and Calspan Report No. 7205-11, "NT-33A In-Flight Simulation of DIANA Session 2 - Landing/Approach Evaluations," by L.H. Knotts and J.E. Priest, December 1985.

3. HUD Symbology Dynamics

Another NT-33 research program in 1985/86 investigated the effects of HUD dynamics and accuracy on pilot performance in various tasks. The variable stability system and programmable Display Evaluation Flight Test HUD system of the NT-33 were used in this investigation. The flight program was used to gather data investigating these display issues. Four evaluation pilots participated in this experiment. The evaluation tasks included up-and-away fighter aircraft maneuver and landing approach evaluations.

The experiment was grouped into two tasks. The purpose of Phase 1, Dynamic Response Requirements, was to investigate the influence of the HUD symbol dynamic response characteristics on manual flight control and flying qualities. This effort focused on the effects of display system computational time delay and computer sampling. The purpose of Phase 2, Symbol Accuracy Requirements, was the investigation of pilot performance and judgement during the IMC to VMC transition for landing using the HUD. This effort examined various contact analog runway displays for the instrument approach and landing task and also, the potential hindrance caused by the display in the transition to visual flight reference. The evaluation included intentional inaccuracies in the projection of the HUD displayed runway symbology as it appeared to overlay the actual runway. In this manner, the pilot's ability to transition from the HUD to outside-the-cockpit, visual flight reference was tested under varying degrees of accuracy for which sensors can determine aircraft position and attitude.

The task reports were Calspan Report No. 7205-14, "Investigation of Head-Up Display Dynamic Response and Symbol Accuracy Requirements (HUD)," by R.E. Bailey, August 1986 and Calspan Report No. 7205-29, "HUD Study II," by R.E. Bailey, October 1988.

4. Effect of Controlled Surface Actuator Rate Limit, Bandwidth, and Time Delay on Aircraft Handling Qualities

In the spring of 1985, the NT-33 was used to determine the actuator requirements for VISTA using piloted in-flight simulations for a matrix of actuator parameters. Two roll control, two pitch control, and two combined pitch and roll control tasks, including landing approaches, were flown as piloting tasks. Pilot perceived differences in handling qualities were recorded for back-to-back comparisons of actuator configurations. A strong correlation was found between lowering a surface actuator rate limit and pilot perception of differences in handling qualities. Pitch control handling qualities appear more sensitive to variations in rate limit than do roll control handling qualities. Roll control handling qualities for the landing task appear more sensitive to variations in rate limit than do the up-and-away roll tasks. Roll control handling qualities for an air-to-ground task are the least sensitive of all to rate limit variations. Depending on the type of task, small differences in handling qualities were noted about 15 percent of the time with actuator rate limits from 25 to 50 percent below the maximum rate normally used by the pilot.

The final report was Calspan Report No. 7205-15, "Investigation of the Effect of Controlled Surface Actuator Rate Limit Bandwidth and Time Delay on Pilot Perception of Aircraft Handling Qualities," by J.R. Easter, March 1987.

5. Time Delay Studies

This research program investigated the effects of control system time delay on manual flight control and handling qualities. The objective was an understanding of how time delay affects ground-based flight simulation. An in-flight experiment and its ground-based replication provided the requisite data for this task. The program results are expected to be used in the formulation of criteria and guidelines for the design and use of ground-based flight simulators.

This work was sponsored in a cooperative effort by the Air Force Human Resource Laboratory, the Flight Dynamics Laboratory, Aeronautical Systems Division, and the Aeromedical Research Laboratory. Four generic aircraft configurations were mechanized which spanned the range of possible ground-simulation facilities rather than performing an experimental variation of aircraft dynamic response characteristics. Time delays were introduced in both pitch and roll flight control systems. The evaluation tasks were flown in simulated IMC flight. The NT-33 HUD system was programmed to generate a flying qualities test maneuver simulating a tracking maneuver as well as compensatory tracking against sum-of-sines generator input. The latter task was used to derive explicit pilot modeling data for subsequent analysis. Three evaluation pilots performed the evaluations. The NT-33 was also used as a ground-simulation facility to provide a comparison between airborne and fixed-base ground simulator evaluations. This process allowed a ground-based duplication of the in-flight experiment.

The final report was Calspan Report No. 7205-16, "An Investigation of Time Delay During In-Flight and Ground Simulation," by R.E. Bailey, April 1987.

6. VISTA Support

The original VISTA design requirements specified that the safety pilot be provided with tactile stick position cues. These cues would be proportional to the F-16 pilot force commands that would be required to perform the same aircraft maneuvers commanded by the evaluation pilot. The need for tactile cuing had already been established. There was, however, a need for experimental data to support design requirements for the tactile position cuing controllers. The VISTA engage and disengage mechanization, tactile position cue drive, and a simplified F-16 control system were implemented in the NT-33 Rolm 1602 digital computer. The NT-33 VSS feedback loop was used to simulate the pitch and roll characteristics of the open-loop F-16. Thirteen flights were flown to refine the VISTA tactile cue requirements as well as the engage/disengage attributes of the VISTA safety pilot's sidestick.

The final report was Calspan Report No. 7205-20, "An NT-33A In-Flight Investigation into VISTA/NF-16D Tactile Position Cue Requirements," by L.H. Knotts, August 1987.

7. Interaction of Feel System and Flight Control System Dynamics and Lateral Flying Qualities

In the fall of 1988 the NT-33 was used in an in-flight investigation to examine the influence of feel system characteristics on lateral fighter flying qualities. Subjective pilot evaluation and quantitative tracking data were examined. These data showed that 1) the feel system is a unique flight control system element that affects flying qualities whether the system is employed in a force command architecture or a position command architecture; 2) a 26- rad/sec feel system frequency with 0.7 damping ratio is transparent to the pilot; 3) variations in feel-system dynamics are not equivalent to the same variations in downstream flight control system elements; 4) a decreased force-deflection gradient (more stick motion per unit of input force) centerstick controller greatly alleviated roll ratchet tendencies; 5) frequency response analyses of tracking data are not sufficiently indicative of roll flying qualities or roll ratchet tendencies; and 6) airplane motion cues are critical to the accurate evaluation of roll flying qualities. Based on these results, flying qualities criteria were proposed for the design of roll flight control systems. The requirements specify a satisfactory range of effective roll mode time constant, effective time delay, feel system frequency response characteristics, and roll acceleration capabilities. These criteria are required to augment the MIL-STD-1797 requirements which specify minimum roll capabilities rather than maximum capabilities that are being tested in today's fly-by-wire vehicles.

The final report was Calspan Report No. 7205-26, "Interaction of Feel System and Flight Control System Dynamics on Lateral Flying Qualities," by R.E. Bailey, December 1988.

b. TIFS Projects

1. Criteria for Pitch Rate Systems

An in-flight investigation of the performance of pitch-rate command flight control systems in the flared landing task was conducted at Buffalo, New York in September 1983. A shortcoming of these types of flight control systems is the tendency to float during flared landings. This floating tendency results in flying qualities ratings that cannot be consistently predicted by classical predictive criteria. In this program 27 flight control configurations were tested in flight. The configurations included conventional and superaugmented pitch-rate command systems, neutral static stability cases, shuttle-like configurations, a conventional Level 1 aircraft, and configurations that included prefilters to improve flying qualities of pitch rate command systems.

The results of the flight program demonstrated improvements from Levels 2 and 3 to Level 1 performance by use of the prefilters. A lead/lag filter provided more rapid initial responses for better flight path control and a washout prefilter provided monotonic pitch control forces during the flare which are lacking in rate command systems. Various classical frequency domain predictive criterion were applied in the analysis, and a method using the bandwidth criteria closed on altitude-rate (vs. attitude) showed promise. In addition, a Time Domain predictive criterion was developed that appears to improve flying qualities prediction for the flared landing task.

The final report for this task was NASA CR 172491, "Pitch Rate Flight Control System in the Flared Landing Task and Design Criteria Development," by C.J. Berthe, C.R. Chalk, and S.K. Sarrafian, November 1984.

2. An In-Flight Investigation of a Twin Fuselage Configuration in Approach and Landing

An in-flight investigation of the flying qualities of a Twin-Fuselage Aircraft design in the approach and landing Flight Phase was carried out in the TIFS. The objective of this study was to determine the effects of actual motion and visual cues on the pilot when he was offset from the centerline of the aircraft. The experiment variables were lateral pilot offset position (0, 30, and 50 feet) and effective roll mode time constant (0.6, 1.2, and 2.4 seconds). The evaluation included the final approach, flare, and touchdown. Lateral runway offsets and 15-knot crosswinds were used to increase the pilot's workload and force him to make large lateral corrections in the final portion of the approach. Results indicated that large normal accelerations rather than just vertical displacements in rolling

maneuvers had the most significant degrading effect on pilot ratings. The normal accelerations were a result of large lateral offset and fast roll mode time constant and caused the pilot to make unnecessary pitch inputs and get into a coupled pitch/roll oscillation while he was making line-up and crosswind corrections. A potential criterion for lateral pilot offset position effects was proposed. When the ratio of incremented normal acceleration at the pilot station to the steady-state roll rate for a step input reached 0.01 to 0.02 g/deg/sec, a deterioration of pilot rating and flying qualities level occurred.

The final report was Calspan Report No. 7205-4, "An In-Flight Investigation of a Twin Fuselage Configuration in Approach and Landing," by N.C. Weingarten, August 1984.

3. X-29A Terminal Area Simulation

This program provided the X-29A ADPO and Grumman with in-flight evaluation of the expected handling qualities of the X-29A well in advance of first flight. The simulation emulated the all-up digital flight control system, the digital reversion mode, and the analog reversion mode.

The preparatory effort consisted of digital flight control system modeling and programming, digital representation of the low speed aerodynamics, analog mechanization of the analog reversion mode, check solution programming, and evaluation cockpit preparation. The simulation of the X-29A aircraft was one of the most complex ever produced in TIFS. Aerodynamic coefficients were computed using 56 table look-up routines consisting of 20 functions of 3 variables, 18 functions of 2 variables, and 18 functions of 1 variable. The cycle time was 25 msec for the equations of rigid body motion and 12.5 msec for the digital control system equations and logic as it is in the actual X-29A system.

The results indicated that 1) a 35 percent mean aerodynamic chord unstable airplane can be successfully stabilized and flown; 2) the original flight control system design was prone to roll PIO in all FCS modes due to abrupt roll response, the PIO tendency could be reduced somewhat by pilot control technique; 3) the thrust response was extremely high to pilot throttle input; 4) speed stability was satisfactory and a speed stabilization FCS mode was not required; 5) turbulence response was extreme and should be a major concern; and 6) X-29 flying qualities may not be forgiving; thus only experienced test pilots should be allowed to fly.

Based on these results, two changes were made to the X-29A flight control system. First, roll command and roll feedback gains in digital FCS were reduced to alleviate roll abruptness. Second, the throttle quadrant was modified to reduce the thrust response sensitivity. In addition, the flight test program was tightly structured in the initial flights to avoid turbulence, avoid crosswind/gusts, evaluate the analog flight control system mode flying qualities at altitude, and ensure training/familiarity by requiring up to three ground simulation sessions prior to a flight.

Analytical studies included an investigation of sidestick controllers, an assessment of Boeing flying qualities criteria, a review of the 7J7 flying qualities, and a review of the benefits of ground and in-flight simulation in the development of control systems and displays.

The TIFS was used to evaluate the Boeing 7J7 control systems, displays, and controllers in the actual flight environment. Two flight simulation evaluation sessions were flown. Session I was flown during January and February of 1987. Session II took place during May of 1987.

Session I was used to investigate the enhanced mode during landing approach to touchdown and the backup mode during cruise and landing approach. A Boeing 7J7 simulation was also mechanized to provide a known baseline conventional configuration to which comparisons could be made. An inertial navigation system was installed to provide sensor inputs to the enhanced control system.

In addition to the development and evaluation of the various flight control systems, the major objective of Session I was to evaluate the relative merits of small and large displacement cockpit controllers. To achieve this objective, small sidesticks were installed in the TIFS evaluation cockpit, one at the pilot's left side and one at the copilot's right side, in addition to a conventional wheel/column which was installed only at the copilot's station. Direct comparisons could then easily be made between control with the sidesticks or the wheel/column. Operational effects of dual controller inputs or contention from simultaneous commands from both left and right pilot stations were also investigated. Actual aircraft electronic displays were also installed to evaluate various proposed formats.

The final reports were Calspan Report No. 7205-17, "Boeing 7J7 Simulation in the Total In-Flight Simulator," by N.C. Weingarten, K.S. Govindaraj, and P.A. Reynolds, April 1987 and Calspan Report No. 7205-19, "Boeing 7J7 Simulation in the Total In-Flight Simulator (Session II)," by N.C. Weingarten, K.S. Govindaraj, and P.A. Reynolds, June 1987.

10. Evaluation of Shuttle Training Aircraft System Modification

The objective of this project was to review the winds measurement system proposed for the Shuttle Training Aircraft (STA). Tasks included reviewing the accuracy of the proposed wind computational algorithms, aircraft sensor and calibration requirements, safety considerations associated with the injection of the measured winds to the Orbiter model, and demonstration on the TIFS aircraft of the feasibility of measuring winds during maneuvering flight.

Results included the definition of the correct algorithms for measuring winds, air assessment of the instrumentation calibration requirements, and recommendation for improvement of model-following fidelity and flight of the TIFS to demonstrate the accuracy to

which the ambient winds can be measured in a maneuvering aircraft was also accomplished. Many recommendations were made with the objective of improving the Orbiter simulation fidelity by the STA resulting in enhanced astronaut training and improved STA flight safety.

The results were documented in USAF/FDL Total In-Flight Simulator (TIFS) Technical Memorandum Number 1401, "STA/Orbiter Winds Evaluation," by T.C. Joseph, S.A. Buethe, and E.G. Rynaski, September 1987.

5. RESULTS FROM CURRENT GERMAN WORK

5.1 Task I

a. Development and Flight Testing of GRATE - Ground Attack Test Technique

Dynamic handling qualities of aircraft can be tested by a pilot with application of a three-step technique as follows:

- The pilot determines the response characteristics of the aircraft by moving the controls and watching the aircraft response.
- He compares the dynamic behaviour of the aircraft with other airplanes.
- He assesses the differences with regard to the importance of the characteristics for a mission or flight phase.

DLR developed and tested the new flight test technique GRATE in consideration of the three steps mentioned. In this technique light targets are placed at different positions on the ground (Fig. 19). During a prolonged dive the lights are switched by an input signal to generate aiming errors in the sights of the head-up display (HUD).

In order to investigate system responses to small perturbations, the targets were placed within a narrow area on the ground.

The distribution of the targets on the ground is designed in the MIL-plane which is perpendicular to the line of sight from the pilot to the centre of the target area (Fig. 20). As the light target arrangements are defined by the task, various arrangements were investigated such as target configurations A and B in Figure 20.

Configuration A was designed to yield a symmetric picture in both the vertical and lateral directions. A random signal creates similar and uncorrelated aiming errors in the vertical and lateral direction.

The target configuration B was selected from several arrangements to obtain a desired step size at any location within the test range of a dive.

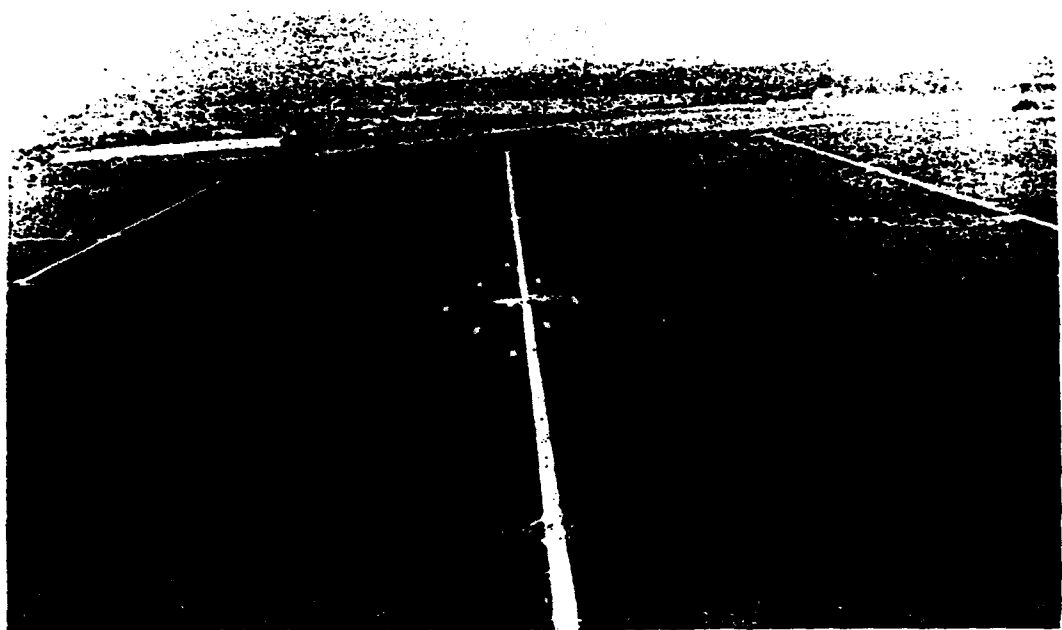
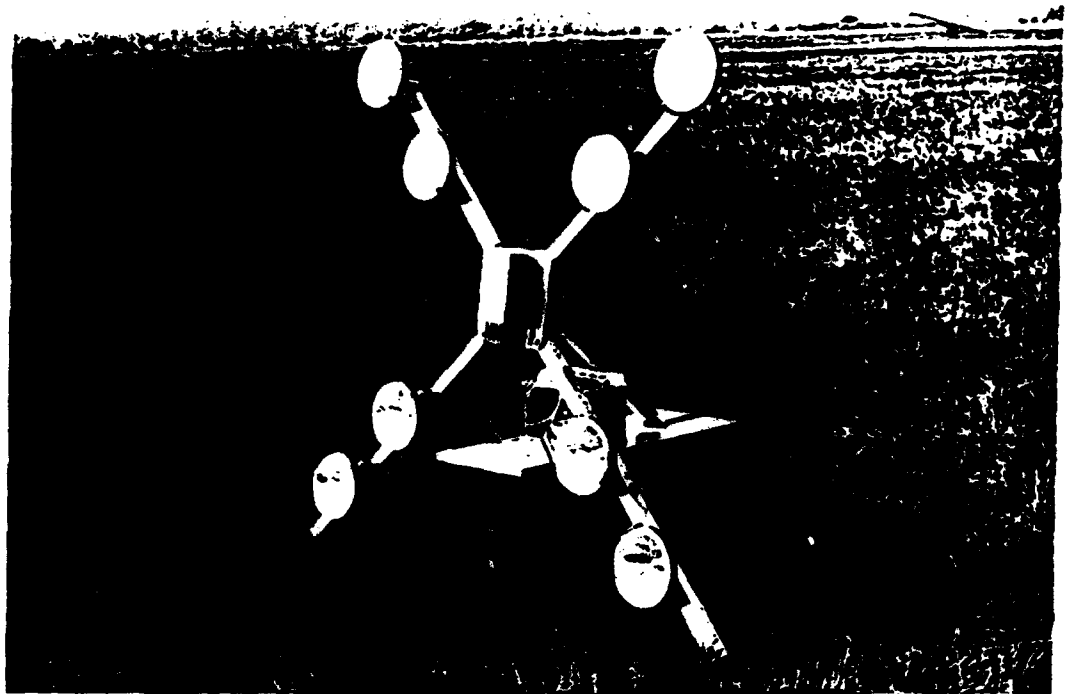


Fig. 19 Arrangement of Target Lights on Ground

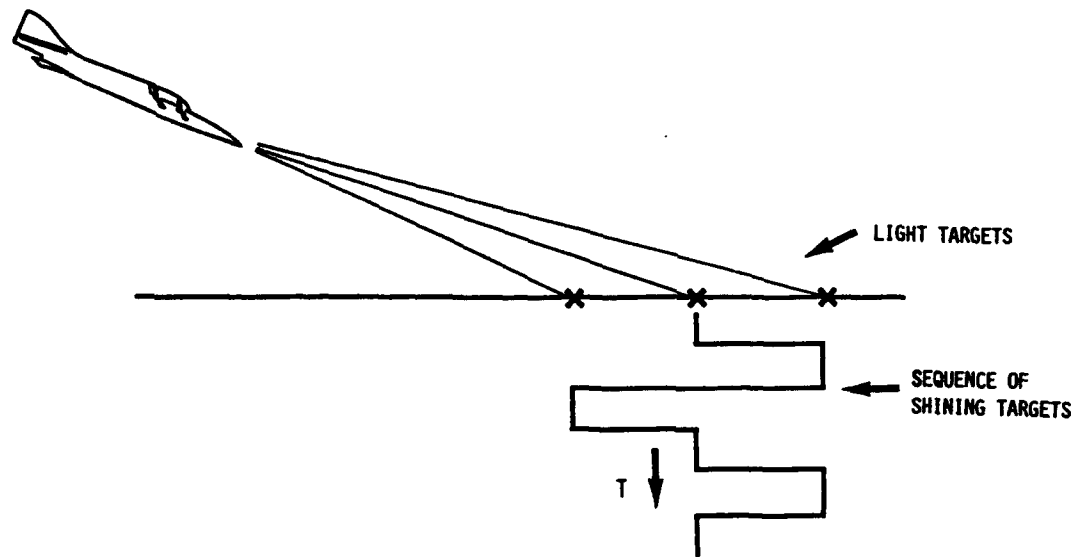


Fig. 20 Modified Air to Ground Tracking Task

In order to evaluate or identify aircraft handling qualities from closed-loop tests, sufficient excitation or disturbance must exist over a reasonably wide bandwidth. The input signals of GRATE are generated by the motions of the line of sight between the pilot and the targets when the lights are switched. They are designed in the time and in the frequency domain.

The basic idea and the test layout of the GRATE-technique were mainly based on theory. Flight and simulation tests were performed to adapt the method to the demands of practical operations. Hence the test pilots had to fulfil various tasks:

- they had to track the targets for data collection;
- they had to provide information about different aspects of the test method; and
- they had to assess the flying qualities of the aircraft using the well-known Cooper-Harper rating scale.

Simulator evaluations were conducted in WRDC's LAMARS moving-base simulator with the GRATE technique.

The purpose of the simulation was to evaluate the GRATE by varying flight configurations with known handling qualities in a precise and repeatable manner. Different levels of time delay and turbulence intensity were investigated relative to the baseline configurations of a ground attack and a fighter aircraft.

Table 1 summarizes the results of varying time delay and turbulence levels for the fighter configurations. Predictably, the effect of increasing time delay was to induce closed-loop oscillations in both pitch and yaw axes. By reading the ratings horizontally, it is concluded that the GRATE for no turbulence is as effective as the application of turbulence in identifying degradations in handling qualities caused by increasing time delays. There is no tendency for increasing turbulence intensity to make ratings worse, at least in terms of the Level rating. The pilot, therefore, apparently rated a qualitative degradation in flying qualities due to time delay which was not significantly affected by turbulence.

Table 1 Turbulence and Time Delay Influence on Pilot Ratings

Pilot Ratings			
time delay (sec)	turbulence intensity (fps rms)		
	none	light (1.5)	mod. (3.0)
0.0	3	3	3
0.1	3/3*	3	-
0.2	4/6	4	5
0.3	7/9**	8**	8**

* "slight pitch bobble for tracking"

** "could not perform task within reasonable tolerance"

To check that the GRATE was truly effective in unmasking poor handling qualities, GRATE was suppressed by flying with all the lamps on. An offset was simulated by transitioning from the closest to the farthest lamp at about 250 meters AGL. The results are shown in **Table 2**. Note that with no turbulence, the offset simulation failed to unmask the degradation in rating due to a time delay of 0.1 sec. For a time delay of 0.2 sec, the offset resulted in a degradation in flying qualities but not to the same extent as with the GRATE. The optimistic ratings for the offset are due to the pilot compensating for time delay and /or turbulence by flying very smoothly, an option which is not available with the high bandwidth input excitations of the GRATE. It is apparent from the last row of **Table 2** that the offset maneuver, even with turbulence, did not consistently unmask flying qualities deficiencies.

Table 2 Influence of Test Techniques on Pilot Ratings

Pilot Ratings				
time delay (sec)	GRATE Technique		Offset Maneuver	
	turbulence intensity		turbulence intensity	
	none	light	none	light
0.1	5	5	2	5
0.2	7	7	4	3

The pilots rated the technique to be well suited for evaluating air-to-ground handling qualities. Results showed that GRATE is effective and easy to both learn and use. It is as effective as turbulence in unmasking poor flying qualities. As turbulence is not available on call, poor flying qualities may remain masked even in an otherwise rigorous conventional test program.

Prior to the LAMARS simulator tests flight tests were performed at the German Armed Forces Flight Test Center WTD 61 in Manching using an Alpha Jet type aircraft.

The evaluation of the flight test data has been concentrated on the investigation of tracking performance parameters.

Flight test data were measured from HUD camera film including position of the pipper and the illuminated lamp (see Fig. 21).

The star-like pattern in the cross plot of the aiming error indicates four loops which correspond to the four steps of the light signal. The time histories of these four sequences can be treated as four isolated characteristic motions with different initial conditions of the pilot-aircraft system.

A mean radial deviation p_r was calculated eliminating estimated disturbance effects (Fig. 22).

The time up to the moment when the mean radial deviation passed the value of 3 mrad was determined and increased by 10 percent. This result was defined to be the align-time.

After the align-time, tracking is approximately a stationary random process. The test data of the stationary tracking can be evaluated by determining a circle which is called circular error probability around the mean aiming point, CEP_{MAP} .

The align-time and CEP_{MAP} are shown in Fig. 23 for different turbulence levels which were determined from pilot comments. Each point in the diagram is an evaluation result of an attack dive.

The align-time may vary if maneuverability characteristics are changed, but obviously it does not depend on the turbulence.

The CEP_{MAP} remains constant in low turbulence levels but increases when the turbulence becomes moderate to heavy.

For comparison of different feedback modes, quantities of CEP_{MAP} were taken with turbulence levels of none to light to moderate.

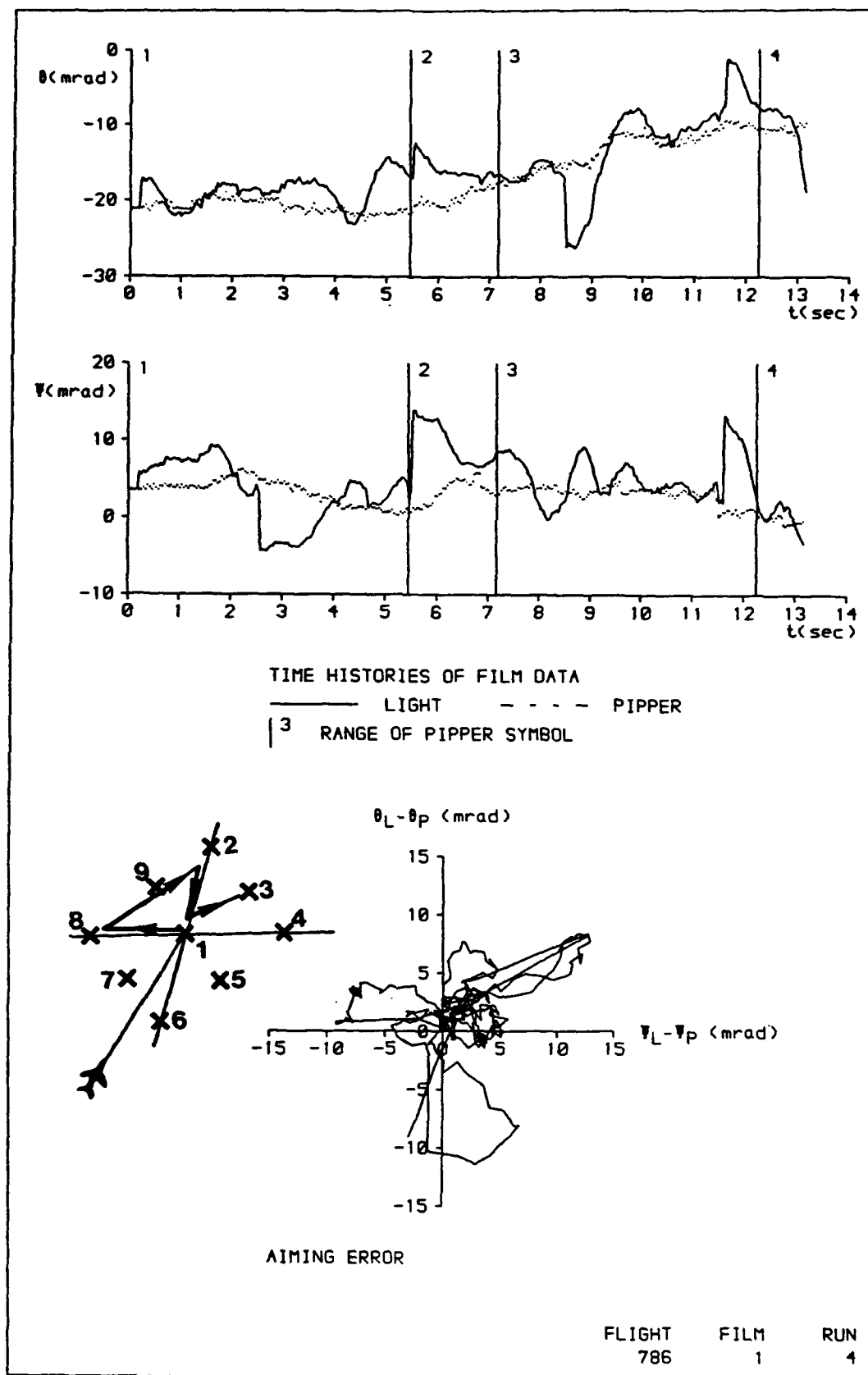


Fig. 21 Plots of Film Data

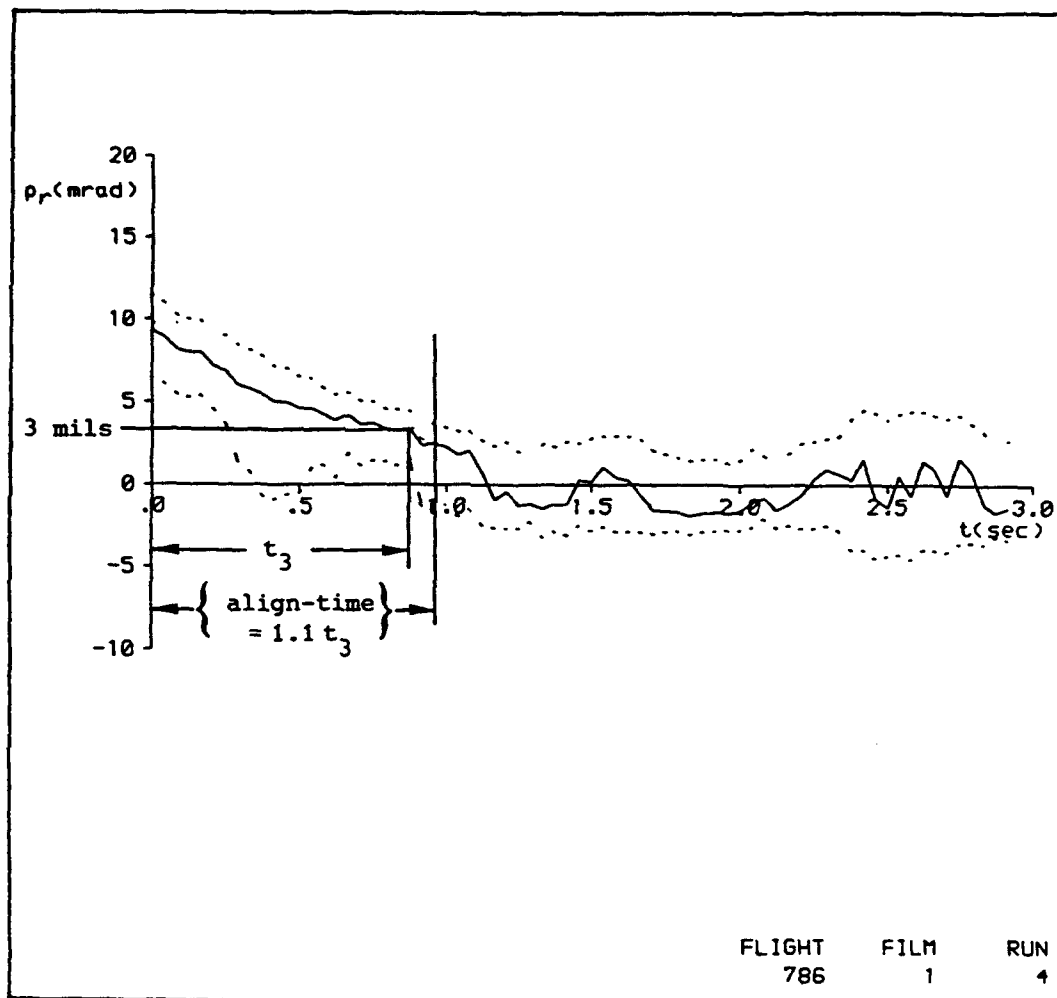
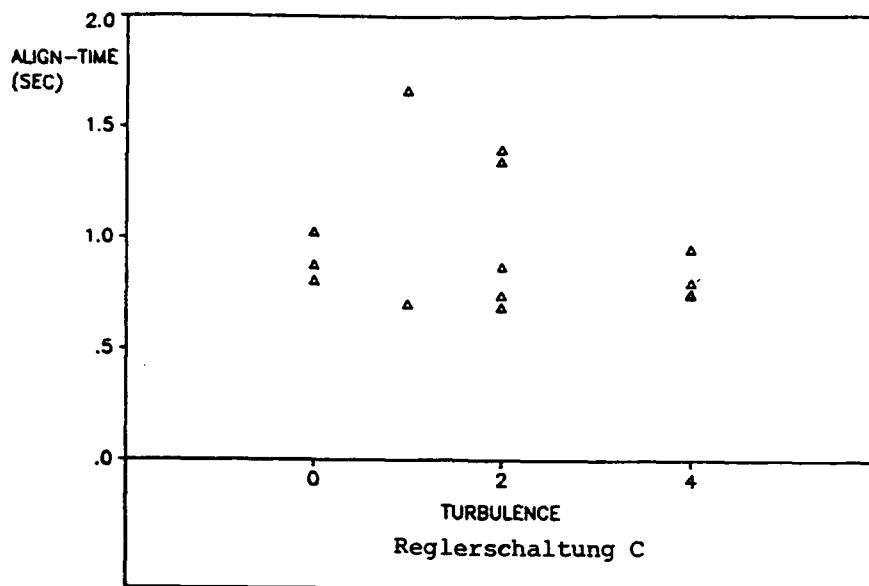
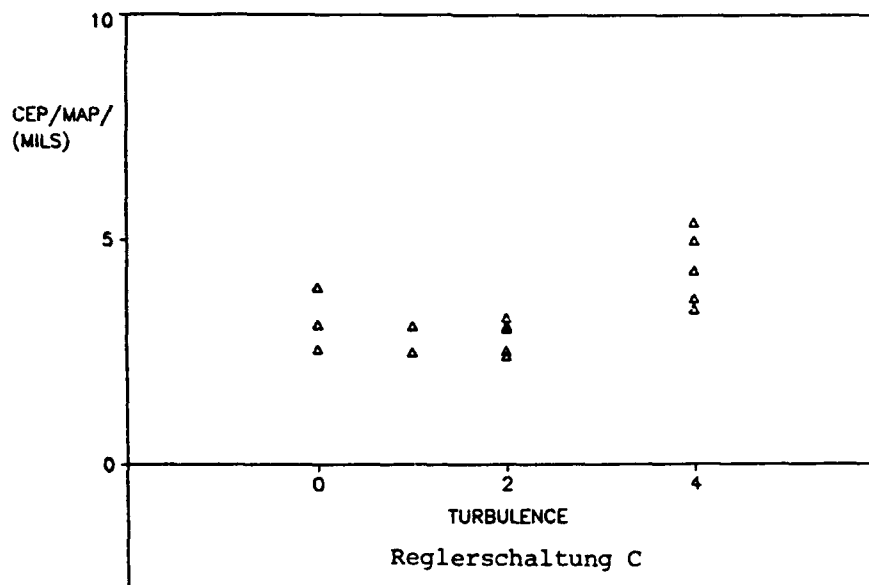


Fig. 22 Time Histories of Mean Aiming Error



TARGETS: COMB.PATT.



TARGETS: COMB.PATT.

Fig. 23 Influence of Turbulence Intensity on the Align-Time and Circular Error Probability

An average of the pilot ratings was calculated and drawn against the mission parameter CEP_{MAP} in Fig. 24.

The values of the feedback modes of B, C, and D yield a straight line. Its slope is a sensitivity of pilot rating.

A change of 1 mil of CEP_{MAP} resulted in a change of 0.5 in the rating of precision tracking.

PIO tendencies of the feedback mode A resulted in a high workload during precision tracking. Therefore the pilot rating increased disproportionately and the dot appears over the line drawn in Fig. 24.

Mean values of the pilot ratings of maneuverability were calculated and drawn against the mission parameter of align-time in Fig. 25. The slope of the straight line is again a sensitivity of the pilot rating.

A change of 0.2 sec in the align-time resulted in a change of 0.5 in the rating of maneuverability.

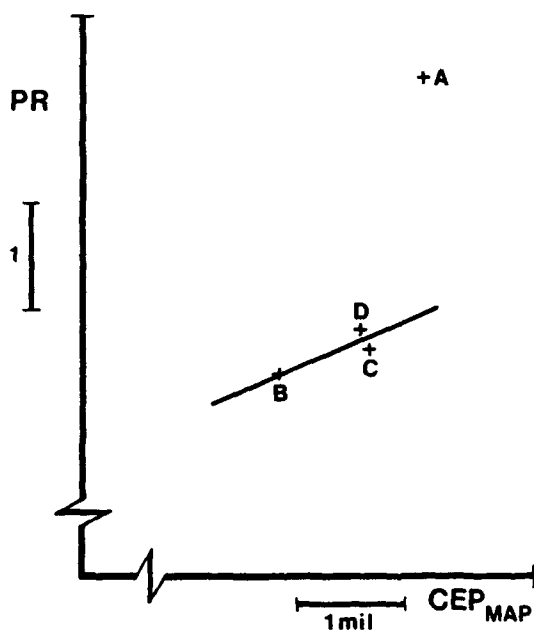


Fig. 24 Mean Pilot-Rating of Precision Tracking Capability vs. Circular Error Probability

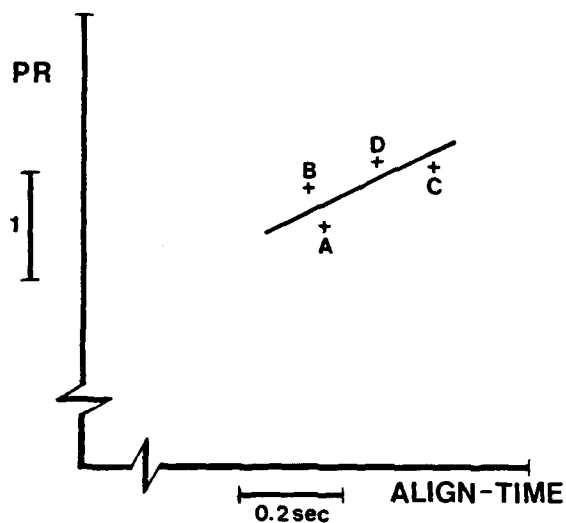


Fig. 25 Mean Pilot-Rating of Maneuverability vs. Align-Time

In October 1988, two flight test programs were performed at Edwards AFB to test NASA Ames-Dryden's Adaptable Target Lighting Array System (ATLAS), which is a derivative of DLR's GRATE system. In addition to DLR and WL/FI, WTD 61, NASA, TPS, and Calspan have been involved in these programs. The first program used the United States Air Force (USAF) NT-33A variability stability aircraft to establish that ATLAS provided a task suitable for use in flying qualities research. A head-up display (HUD) tracking task was used for comparison. An aircraft configuration with good flying qualities was selected and time delays of 0, 90, 130, and 180 msec were added to the flight-control system. When these four configurations were flown using ATLAS, the changes in the flying qualities were perceptible. Fig. 26 shows the pilot rating and time delay, plotted against run number, for one typical sortie. As can be seen, the increase in pilot rating correlates with the increase in time delay as predicted. Six evaluation flights, three for each pilot, were flown in this phase. Fig. 27 shows the average pilot ratings for the ATLAS and HUD tasks. The average ratings for the two tasks agreed well, validating the discrimination of the ATLAS task.

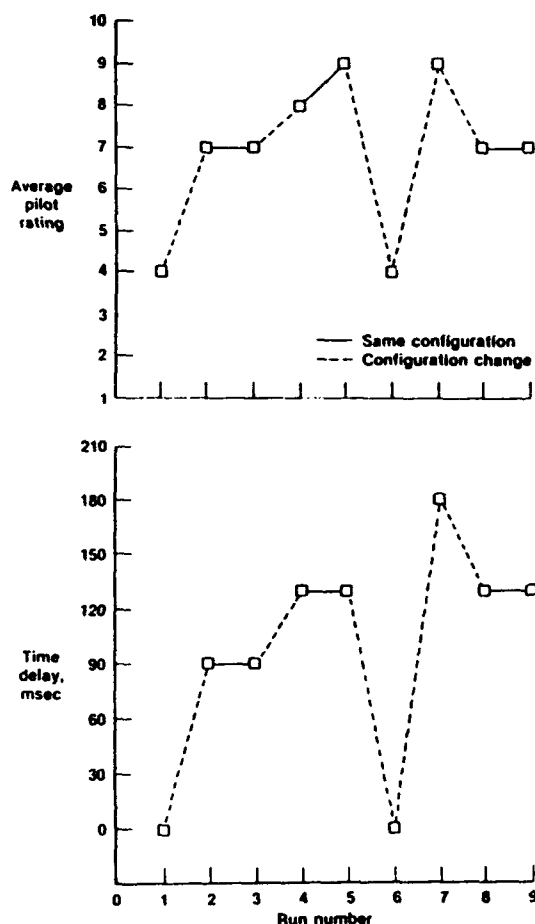


Fig. 26 Pilot Ratings and Time Delay for a Typical NT-33A Flight

The second program used the X-29A forward-swept wing aircraft to demonstrate that the ATLAS task was suitable for assessing the flying qualities of a specific experimental aircraft. In this program, the ground-attack task was used for comparison. All pilots who used ATLAS found it to be highly satisfactory and thought it to be superior to the other tasks used in flying qualities evaluations. They have recommended that it become a standard for flying qualities evaluations.

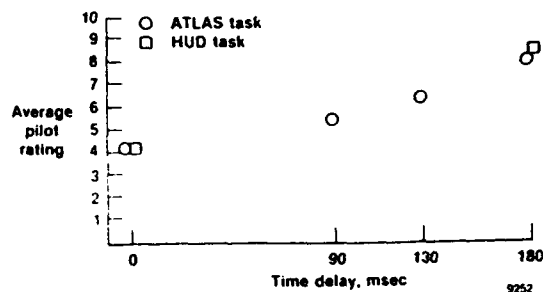


Fig. 27 Summary of Ratings for ATLAS and HUD Tasks

b. Application and Correlation of Handling Qualities Criteria

For the application and correlation of HQ-criteria, methods for the determination of HQ-parameters have been developed. In this field, DLR activities have been concentrated on the definition and development of an Interactive Data Analysis Program Package (DIVA) and a Flying Qualities Criteria Program Package (FMLIB). These systems include the handling of measured time histories, frequency response data, transfer function models and systems of differential equations. With respect to HQ evaluations, the following parts of the program packages are of main interest: The Low Order Equivalent System Approximation (POLYKO), the simulation of linear systems with several time delays, and the options for applying directly HQ criteria like Neal-Smith, Bandwidth, Roeger, Diederich, Gibson.

The evaluation methods were applied in an investigation of the applicability of HQ criteria. For this, two data sets have been used: the data base of the Neal-Smith investigations (57 longitudinal models from AFDL-TR-70-74) and a set of 14 models of an unstable designed fighter-type aircraft. The latter set of models was provided by Dornier during a ground simulation program. The 14 models are based on the same basic airframe characteristics, differing only in the control system design to produce Level 1, Level 2, or Level 3 handling qualities.

Evaluations using both the simulation models and the test time histories were performed by Dornier, DLR, and WTD 61. From these evaluations, the following conclusions could be drawn:

- The direct evaluation of time histories, such as aiming-error cross plots and spectral analysis from air-to-air tracking data, can be helpful tools for the detection of problem areas (e.g., degradation in handling qualities caused by reduced damping).
- During the analytical evaluation of HQ parameters, numerical problems may occur when using iterative computing algorithms. Therefore, the approximation of Low Order Equivalent Systems or the determination of pilot models (for the Neal-Smith Criterion) must be performed very carefully, and the results should be checked visually by the evaluation engineer.
- Time response criteria have shown to be not matured enough for an application in an official HQ assessment. Most of the criteria investigated contain only the limits for Level 1 or for a so-called "Design Aim" instead of limits for all three Levels.
- Open loop frequency response criteria may be helpful as an alternative to LOES-criteria.
- Closed loop criteria (such as Neal-Smith) should be further improved.

Using the simulation results and combining details from the requirements of Diederich and Gibson, a combined Nichols-Plot / Bandwidth criterion for the longitudinal motion could be defined which shows a good correlation with the Neal-Smith data (Fig. 28).

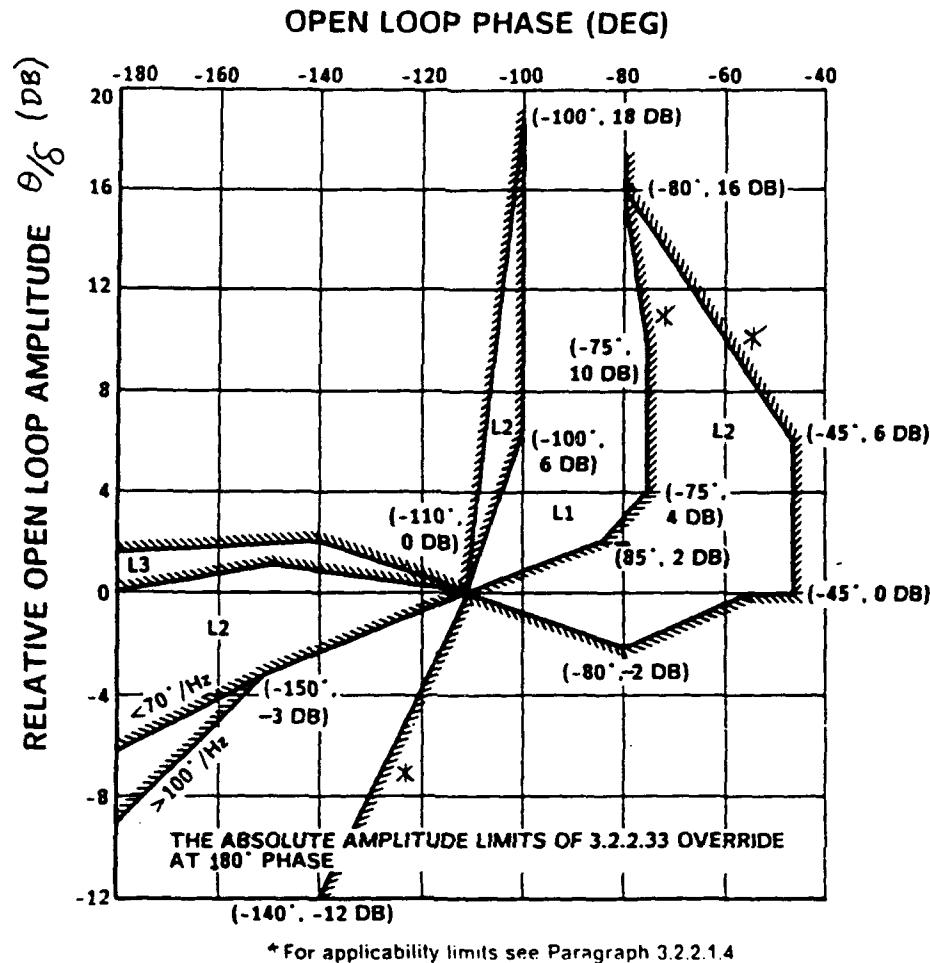


Fig. 28 Pitch Attitude Frequency Response Limits

5.2 Task II

a. Development of ATTAS In-Flight Simulator

Drawing upon experience acquired with the DLR-HFB 320 in-flight simulator, which was successfully used in various handling qualities flight experiments over the last decade, the new airborne simulator ATTAS (Advanced Technologies Testing Aircraft System) has been developed by DLR and MBB. ATTAS is based on the MBB-developed VFW 614 twin-turbofan, short-haul passenger aircraft.

ATTAS will serve as the primary DLR flight test vehicle for research and development to demonstrate and validate new methods and technologies in the area of flight control, flight guidance, navigation, man-machine interactions, and in-flight simulation.

Within the DLR research programs ATTAS will mainly be used as a flying simulator in a broad sense. In this role ATTAS is able to represent the dynamic behaviour of model aircraft or systems under real environmental conditions in total missions providing the pilot with exact visual and motion cues in an early stage of a development. To fulfill all these testing capabilities ATTAS was modified and equipped with a fly-by-wire/light flight control system.

The test equipment, and features of ATTAS are (see Figs. 29 and 30):

- right-hand seat for safety pilot with conventional control system and instrumentation,
- left-hand seat for evaluation pilot with fly-by-wire controls,
- fly-by-wire control column/wheel or sidestick with artificial forcefeel system,
- experimental flight instruments and programmable CRT displays,
- dual digital on-board computer system with fiber-optic data bus,
- dual avionic systems (laser gyros),
- dually-redundant electrical and hydraulic system,
- on-board data acquisition system, recording, and telemetry,
- on-board operator consoles (four stations),
- antenna installation provisions,
- MIL-Bus 1553 B linked self-monitored electro-hydraulic actuators, partly duplex,
- fly-by-wire actuators for
 - elevator,
 - elevator trim,
 - rudder,
 - ailerons (with symmetrical and asymmetrical deflection capability),
 - both engines,
 - landing flaps, and
 - six direct lift flaps (DLC),
- nose boom with α , β , and TAS probe.

To obtain a five degree-of-freedom in-flight simulation capability, ATTAS has been equipped with a specially developed direct lift control system (DLC) for pitch/heave motion decoupling and gust load control. For low frequency DLC operation, the basic VFW 614 landing flap system can be deflected electrically between 1 and 14 degrees. The rear part of the landing flaps has been divided into six (three on each wing) fast moving flaps with an approximate 75 deg/sec flap rate (under aerodynamic loads) and up to ± 35 degrees flap deflection for high frequency DLC operation.

The aircraft is equipped with all sensors necessary to measure the aircraft body accelerations, rates, and attitudes, as well as all control surface positions, pilot command inputs, and engine data. Air data are calculated by two air data computers, inertial data by two laser gyro inertial reference units (LTN 90). Analog sensor outputs are conditioned (amplified, filtered, etc.) in a specially developed signal-conditioning system.

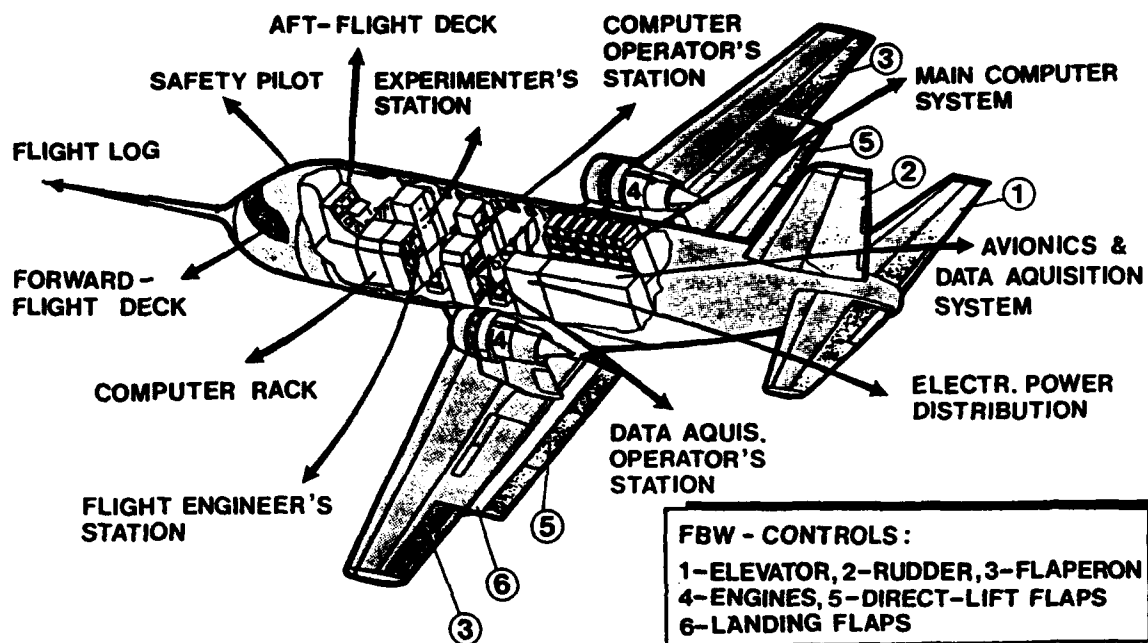


Fig. 29 ATTAS Modification Overview

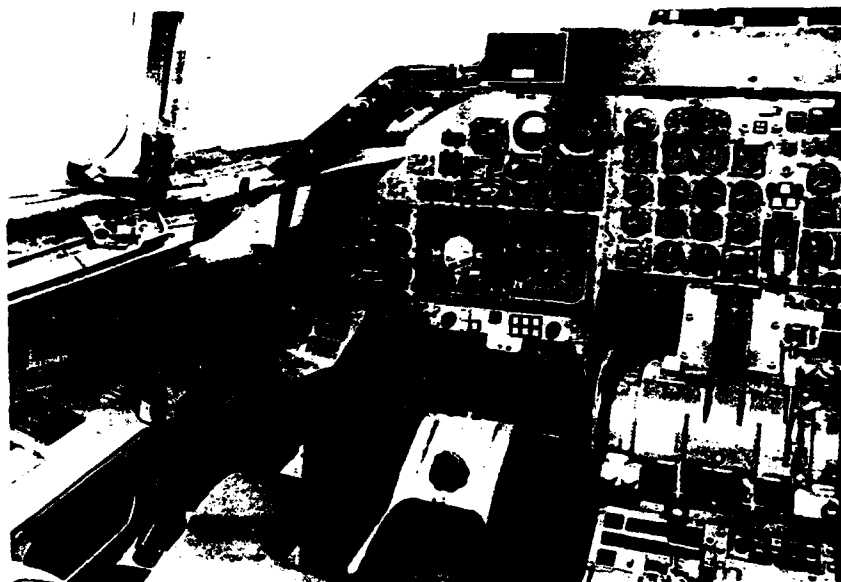


Fig. 30 Simulation Cockpit with 2-Axis Sidestick

For adequate simulation fidelity, high-bandwidth electro-hydraulic serial actuators have been developed for ATTAS. In the primary control axes (elevator and rudder), the basic aircraft boosters are in series with the electro-hydraulic actuators. All 15 actuators are self-monitoring where the monitoring device operates by comparing actual valve position with a modeled valve. The actuator microprocessor-based electronics are housed in four boxes with duo-duplex MIL-Bus remote controllers (RTUs). Due to safety reasons, the elevator and rudder actuators are doubled with duo-duplex failure behaviour (one-fail. op.).

The on-board digital computer system (Fig. 31) provides all the functions needed for system engagement and disengagement, fly-by-wire control laws and limitations, data comparison, data voting and experiment software functions. In-flight simulation with model and controller computation is a typical experiment function.

The fly-by-wire/light control system includes the fly-by-wire controls on the left-hand side of the cockpit. The evaluation pilot's commands are transmitted to the computer system which commands the electro-hydraulic actuators. The computer system itself consists of two computer channels with four computers in each channel and one separate central communication computer. The computers in each channel are linked by a serial fiber-optic bus with a high-speed data transmission rate of 150 KWords/sec in a ring network structure.

The fly-by-wire functions are distributed to the different computers. In the terminal computers (cockpit and aft fuselage) the measured aircraft states are preprocessed, compared, and voted. In addition, they interface with the avionics through the ARINC 429 bus and the actuator electronics through the MIL-Bus 1553 B. The fly-by-wire computer handles the control laws, the mode switching, and the communication with the experimental control computer (ERR) in the simulation mode. The ERR will be used mainly for experimental function computations; therefore, it is a sizeable freely-programmable 32-bit computer with 1.4 MIPS capability and a memory which can be enlarged to 8 MBytes.

All computers, I/O and the fiber-optic serial bus are MIL-Standard equipment. The data processing system is based on ROLM MSE 14 (MIL-Spec Eclipse) 16-bit computers while for the ERR the ROLM HAWK 32-bit computer is provided. All measured and computed data are handled by the central communication computer for on-board tape recording and transmission by PCM telemetry to the ground station.

An essential part of the ATTAS system is the Ground-Based ATTAS-Simulator (Fig. 32) which is a complete copy of the flying ATTAS, simulating all system functions in real-time on the ground. The purpose of the ATTAS-simulator is to develop and validate the fly-by-wire software functions as well as all user-developed experimental programs. The ground-based simulation facility consists of an identical ATTAS cockpit, a nearly identical computer configuration based on commercial computers which are software compatible to the MIL-Spec on-board system, the hybrid computer PACER 600, and the multiprocessor system AD 10/AD 100. The last two computers simulate the complete flight dynamics,

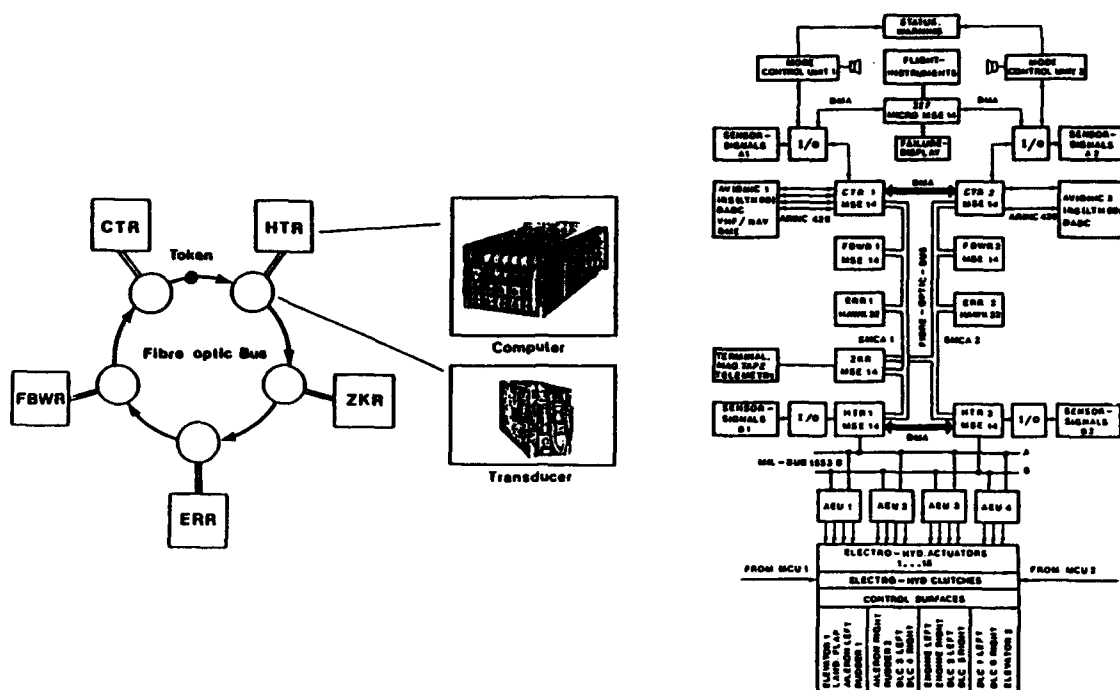


Fig. 31 FBW/Light System Architecture

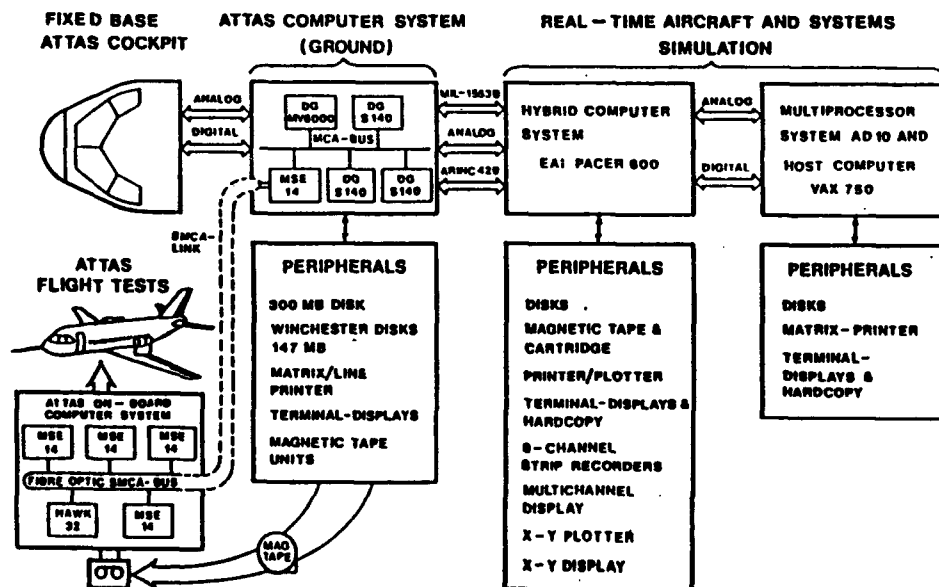


Fig. 32 Ground-Based ATTAS Simulator

actuators, and sensor readings of the aircraft. All sensor output signals and connectors are identical to the aircraft, so that the flight test hardware can be plugged into the simulation. In this manner, all in-flight computer programs can be developed and checked out on the ground under real-time conditions before they are transferred via magnetic tape into the aircraft. Furthermore, the aircraft in the hangar can be linked via the fiber-optic bus with the ground simulator in order to perform a hardware-in-the-loop simulation.

b. Software Development for ATTAS IFS

The software development was organized in a "top down" stepwise method and had to be considered for hardware and software together. From the beginning of the system design software functions were analyzed and designed in parallel to the hardware design in progress. With the structure of the data processing system, the functional structure of the software was defined and resulted in the Software Requirements Document (SRD).

Mainly the involved subsystems and their interfaces (ARINC, MIL 1553 B) specified the requirements to be fulfilled by the software. Also user requirements for minimum controller cycle time and computing power with reusable software had to be considered.

According to the design of the data processing system three main software functions can be identified to be embedded in the computer network:

- Input/Output Operations (Terminal Computer Functions)
- Fly-By-Wire and Experimental Functions
- Communication Functions with different subsystems.

Input/Output Operations are installed in the Cockpit and Tail Terminal Computer (CTC, TTC). They include the interface drivers, data checks with the second channel, scaling and data communication to the parallel processors in the network. Synchronization of all components is done with a Programmable Interval Timer (PIT) interrupt in the cockpit terminal computer program.

Fly-By-Wire Functions are mainly installed in the FBW Computer (FBWC) to fulfil all operations of the FBW control law. The software structure has to consider timing requirements and switching problems as well as special monitoring functions.

User functions are installed in the Experimental and Control Computer (ECC) to give free space and full performance for experimental programs. With the chosen program structure user programs can be included without changes in the operating system and to the runtime structure.

Communication Functions include the interfacing to the telemetry system, data recording on magnetic tape, quicklook presentation on displays, program loading, and offline handling. Functions, being not essential for fail passive behaviour of the FBW control system, are installed in the single Central Communication Computer (CCC) which communicates with all computers in both channels in the duplex data processing system.

Special test procedures were evaluated for ATTAS according to the basic aircraft maintenance and test instructions. The ATTAS test concept therefore divides into two phases, "Ground" and "In-Flight" tests.

Standardized ground tests are performed in periodical intervals or in preflight checks. In-flight tests are normally included in the evaluation program for user flight tests.

The ground tests are performed as so called "Firstflight" and "Preflight" checks.

For Preflight checks the data processing system is involved in all parts needed for fly-by-wire control functions. The program functions cover all modes and switching conditions to obtain full scale of test conditions. The GTRs (Ground Test Requirements) documents give detailed information on how tests have to be performed and how they fit in the basic aircraft checks and operations.

Firstflight checks are also defined in GTR documents organized in different parts to check out single components of the equipment independently. An advantage of using the on-board computer system in check out procedures results in data recording and presentation and, of course, both hardware and identical software can be checked in connection.

After implementing the data processing system different vendor systems were tested in flight and tuned to reach an operational status. Also experiments for parameter identification and calibration of the measurement equipment were carried out.

The ATTAS safety system is based on the safety pilot and his basic-hydraulic mechanical control system. During flight test, it was demonstrated that the safety pilot could under any condition and without any problem take over control. This safety concept is referring to the highest authority of the safety pilot. This is assured by limitations in the actuator forces so that in a runaway failure case, the most critical resulting flight loads, attitudes and rates do not lead to a flight situation reaching the envelope boundaries.

The FBW control system acceptance and validation flight test program covered the mode switching functions, flight control functions, switching transients, recovery procedures due to actuator mode evaluation and the fly-by-wire operation in general. Switching and transient functions occurring by switching between FBW-and BASIC-mode operation have been of main interest.

The FBW operation was tested throughout the complete flight envelope, which is presently limited to a minimum altitude of 500 ft above ground due to safety reasons.

c. Mathematical Modeling of ATTAS Aircraft System

In order to obtain precise information about the complete ATTAS aircraft system, special system identification flight tests were carried out. The flight test data were evaluated using a sophisticated DLR-developed Maximum Likelihood (ML) Identification Procedure for the estimation of parameters in nonlinear systems.

The identification of the different subsystems (actuators, engine, thrust model, etc.) is an important and necessary task when utilizing an aircraft as an in-flight simulator. Two examples will be given dealing with the aileron control system and the DLC-flap actuation system of ATTAS.

The electro-hydraulic actuators of the aileron control system deflect control tabs which are connected to the ailerons with a torsion spring. In this way, the aileron is deflected by the mechanical spring force and the aerodynamic force produced by the deflected control tab. The left and right ailerons are connected with each other and with the column by cables.

The time histories in Fig. 33 show a cutout of results of a joint evaluation of four single flight tests performed at increasing airspeeds. The well-known 3211-input signal was applied for excitation. Fig. 33 presents the comparison of the measured actuator output signal with the output signals of different mathematical models describing the control system dynamics.

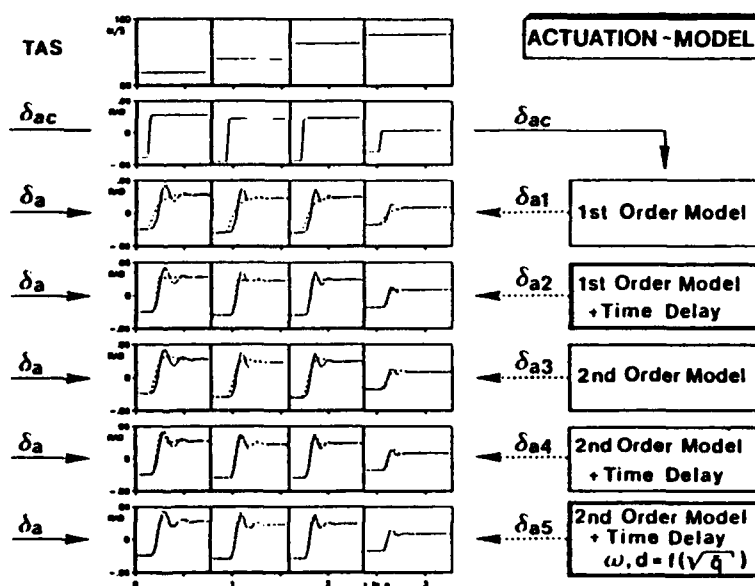


Fig. 33 Identification of the Aileron Control System

The evaluation started with a simple first-order model and ended finally with a nonlinear second-order model. The equivalent time delay substitutes for higher-order dynamics, whereas the dynamic pressure consideration represents the changing aerodynamic forces due to control flap deflection.

For the identification of the dynamics of the DLC-flap system, the mean value of the six single flap deflection angles was calculated applying a weighting factor depending on the individual DLC-flap area. Again different mathematical models were used. The best results were finally obtained with a nonlinear second-order system which, in this case, took into account limitations in the deflection rate and amplitude (Fig. 34).

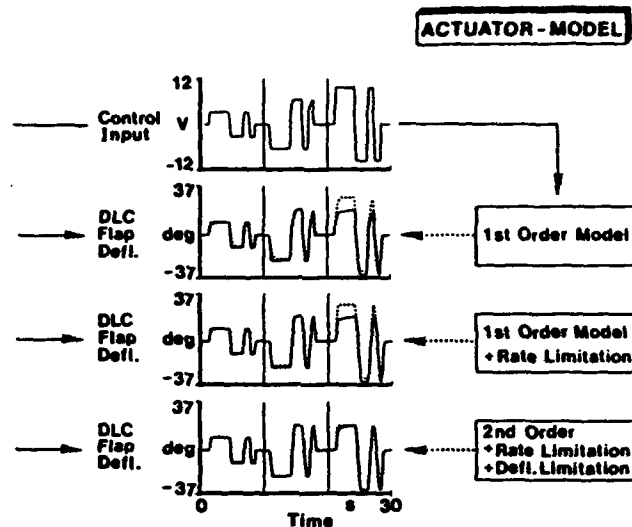


Fig. 34 Identification of the DLC-Flap System

The aerodynamic efficiency of a control surface is only identifiable using the entire dynamic response of the aircraft, since the aerodynamic forces and moments are not directly measurable. In order to determine nonlinear control effectiveness, it is necessary to excite the system with inputs of several different amplitudes or with inputs at different reference control surface positions.

An example is given in Fig. 35 showing the efficiency of the DLC-flaps at three different landing flap positions. The curves belonging to the 14° landing flap position show two remarkable differences to the two others:

- the DLC-flap deflection does not exceed about 23° due to the forementioned force limitation of the actuators, and
- the DLC-flap efficiency is obviously reduced due to flow separation already at low positive DLC-flap deflections (trailing edge down).

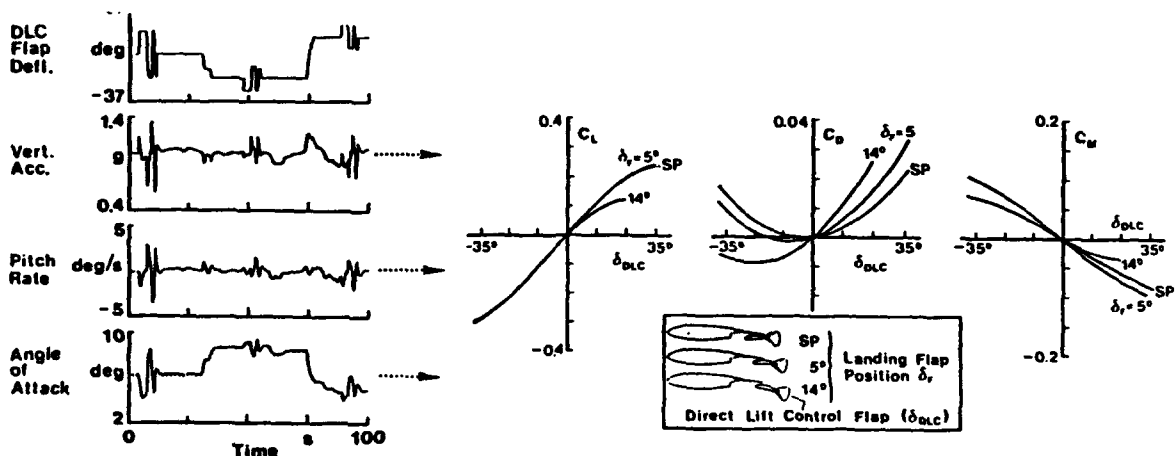


Fig. 35 Identification of the DLC-Flap Efficiency

To model the nonlinear characteristics, quadratic and cubic mathematical model structures for the aerodynamic coefficients were used. The latest results were obtained applying the nonlinear ML-procedure to flight data recorded during flight tests with excitations of the aircraft motion in all six degrees of freedom (6 DOF-System Identification). In the system identification process a nonlinear two-point model was introduced in which aerodynamic lags and cross-coupling effects can be considered.

Based on the experiences gained with the former HFB 320 in-flight simulator DLR designed an improved explicit Model-Following Control System for ATTAS that takes into account the model structure of the actuator dynamics of the VFW 614 host aircraft (Fig. 36).

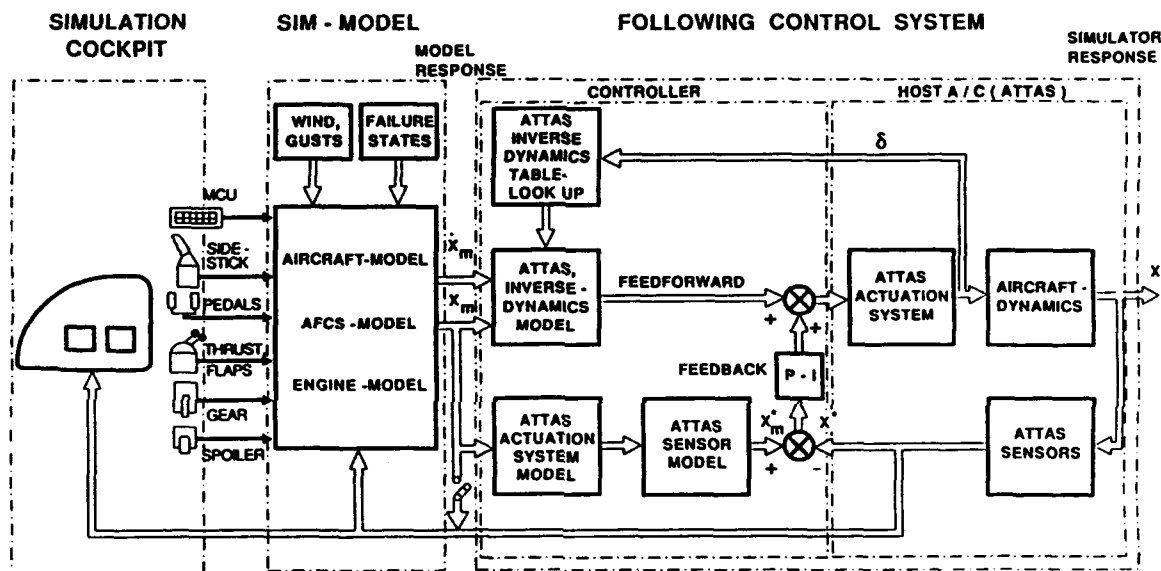


Fig. 36 ATTAS In-Flight Simulation System

The feedforward control scheme yields gains which are independent of the model parameters and, thus, depend only on the host aircraft characteristics. Robustness properties of the DLR model-following concept have been achieved by implementing time and frequency domain criteria in the vector performance optimization.

The in-flight simulation performance and fidelity was demonstrated on various models like Airbus A300, N250, and HERMES spaceplane. A typical comparison of model and ATTAS response fidelity is shown in Fig. 37 presenting the roll response of a HERMES type spaceplane.

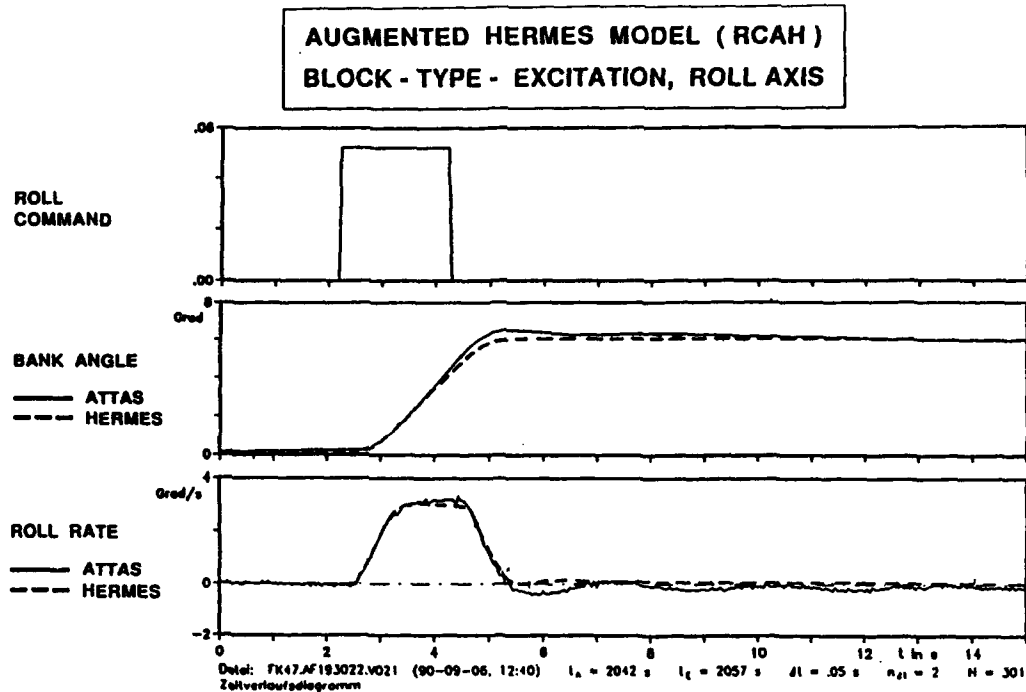


Fig. 37 ATTAS IFS-Flight Test Results

Additionally, a general dynamic simulation capability criterion was developed defining the matching capability as a function of frequency and the phase delays of both, the host airplane and the model to be simulated (Fig. 38), (see also Ref. 23).

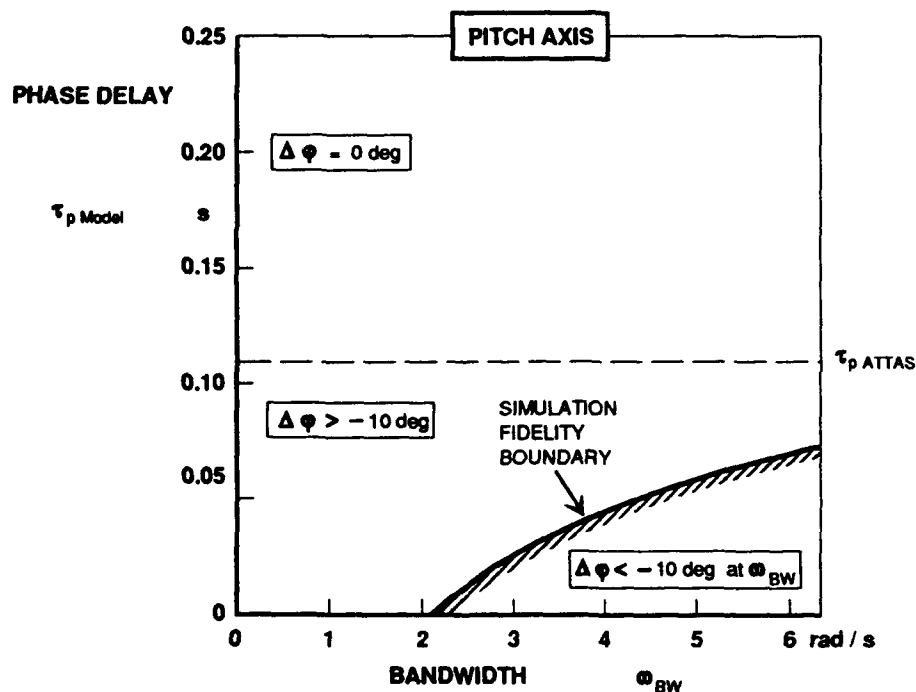


Fig. 38 ATTAS Dynamic Simulation Capability

6. CONCLUSIONS

For some years, DLR and WL/FI have cooperated in research on aircraft flight control, specifically on two tasks:

Pilot-in-the-loop flying qualities:

- Pilot-vehicle analysis,
- Handling quality correlations,
- Flight test techniques for handling qualities investigation;

In-flight simulation methodologies:

- System configurations and elements,
- System identification for flight control optimization and modeling,
- Pilot evaluation methodologies.

As exemplified by the new US MIL-STD-1797, flying qualities requirements still are best expressed, generally, in terms of vehicle characteristics rather than pilot-in-the-loop parameters. Pilot-vehicle analysis, however, is an increasingly powerful tool for developing requirements, and also for aircraft/flight control system design. Models based on either classical or modern control theory can be helpful:

- Multiaxis pilot control and the effects of distractions from piloting can be analyzed using a simple model of divided attention.
- Display dynamics, long neglected, can affect pilot opinion and pilot-vehicle performance significantly. Pilot modeling can be used with modern control theory to optimize display dynamics.

Analyses of approach and landing have found a number of useful criteria and design helps:

- Good dynamic separation of pitch and flight-path responses, characterized by the effective value of the pitch zero $1/T_{\theta 2}$, is essential for either series or parallel pilot closure of these two control loops.
- A step-like response of angle of attack to a step command, corresponding to a k/s-like path response to pilot commands avoids a possible piloting problem in correlating pitch and flight-path responses. With proportional-plus-integral control, that consideration requires the integrator time constant to have a value close to $T_{\theta 2}$.
- Control sensitivity affects the satisfactory range of aircraft dynamic response parameters. The most recent criterion bounds a region in the plot of flight-path-to-control-force magnitude at crossover versus flight-path bandwidth.
- For STOL landings, an attitude command/attitude hold control law appears best; but, given a sufficiently high bandwidth, a conventional rate response type is acceptable.

With emphasis on agility, describing nonlinear flying qualities becomes more important. In preliminary studies, several approaches show promise:

- Truncated Volterra series,
- Dynamic inversion,
- Differential geometry.

The DLR GRATE sequenced-light array provides an excellent means of evaluating aircraft handling qualities in ground attack.

It is possible to consider flying qualities requirements directly in the design of a flight control system. Current and additional work are needed, however, to better bring flying qualities considerations into the design process, which now includes many more integration aspects.

A new flying simulator ATTAS was developed at DLR from 1982 to 1986. This aircraft is equipped with modern systems to be able to cope with the requirements at least over the next decade. The model-following system developed for in-flight simulation or variable stability capabilities proved as excellent and its performance was checked against different types of aircraft and tasks. Also the concept of having a complete ground base system simulator of ATTAS in order to prepare and validate the flight test software and procedures turned out as very valuable by improving flight test operation. Additional work is needed to expand the flight envelope in the FBW or simulation mode to touchdown.

7. RECOMMENDATIONS

The DLR and WL/FI handling qualities research programs are complementary. While many flying qualities criteria need to be tailored to specific mission-oriented tasks, a number of elements remain common among diverse tasks and aircraft classes. For example, in some respects the critical landing tasks are the same for transport and fighter aircraft. By cooperating in planning, and by sharing results, each organization benefits from the other.

The flying simulators of WL/FI and DLR are different because different host aircraft are used and different technical solutions have been selected. On the other hand, the methodology in performing in-flight simulation is very similar. Further, in TIFS, NT-33, and also VISTA, the same on-board computers are used as in the ATTAS. So the exchange of experiences by using these computer systems and ideas to improve the simulation fidelity, to improve operational procedures are of particular value and could be fruitful for both sides.

Joint projects such as the American adaptation of DLR's GRATE method of flying qualities assessment to its own simulator and flight test use are of particular value and should be continued. Cooperation in the development and usage of each other's in-flight simulators is another fruitful effort worthy of extension.

Possible additional topics for research cooperation are:

Pilot-vehicle integration:

- Flight test techniques for handling qualities investigations,
- Handling qualities correlations,
- Display dynamics for good flying qualities,
- Control design techniques with integrated flying qualities criteria,
- Nonlinear flying qualities metrics;

In-flight simulation methodologies:

- System configuration and elements,
- System identification.

APPENDIX A: ABSTRACTS OF DLR TECHNICAL DOCUMENTS

- (1) Koehler, R., Buchacker, E., "A Flight Test Method for Pilot /Aircraft Analysis," in: NASA CP 2428 (1986), pp. 35.1 to 35.14, 12 figs., 3 refs.

To investigate the dynamic behaviour of the pilot/aircraft system a special ground attack flight test technique with a prolonged tracking maneuver has been developed.

By changing the targets during the attack, the pilot is forced to react continuously on aiming errors in his sights. Thus the closed-loop pilot/aircraft system is excited over a wide frequency range of interest, the pilot gets more information about mission oriented aircraft dynamics and suitable flight test data for a pilot/aircraft analysis can be generated.

This report includes

- general description of the test equipment,
- input signal design,
- flight test program,
- first results of an evaluation.

- (2) Koehler, R., "Simulator Tests of Air-to-Ground Tracking," DFVLR-FB 87-05 (1987), 34 pages, 21 figs., 4 refs.

Aiming during ground attack is an extremely demanding task and excellent flying qualities are required for precise tracking of the target. A method for assessing flying qualities by pilots and for measurement of mission parameters was tested in a five-degrees-of-freedom simulator. A short description of the method along with first evaluations of the pilot comments are presented.

- (3) Koehler, R., Buchacker, E., Biezd, D.J., "GRATE - A New Flight Test Tool for Flying Qualities Evaluations," AGARD FMP 73rd Symp. "Flight Test Techniques," Edwards AFB, Cal. (USA), Oct. 17-20, 1988.

In this paper a description of the flight test method and of the pilots' role and ratings is given. Head-up-display films have been evaluated to determine a so called line-up-time (LUT) and a circular error probability (CEP). The influence of different test conditions on the mission parameters has been investigated. The results of the numeric analysis and the pilot ratings have been compared. The determined gradients show the sensitivity of a pilot rating to the mission parameters. In this context a configuration with slight PIO-tendencies is discussed.

Simulator tests have shown that the technique is an effective tool to sort out aircraft handling problems. The effects caused by different turbulence levels on pilot ratings were found to be small in comparison to conventional methods.

- (4) Shafer, M.F., Koehler, R., Wilson, E.M., Levy, D.R., "Initial Flight Test of a Ground Deployed System for Flying Qualities Assessment," NASA Technical Memorandum 101700, AIAA Pap. 89-3359 (1989), 7 pages, 8 figs., 1 tab., 6 refs.

In order to provide a safe, repeatable, precise, high-gain flying qualities task, a ground deployed system was developed and tested at the NASA Ames Research Center's Dryden Flight Research Facility. This system, the adaptable target lighting array system (ATLAS), is based on the German Aerospace Research Establishment's ground attack test equipment (GRATE). These systems provide a flying-qualities task, emulating the ground attack task with ground deployed lighted targets. These targets light in an unpredictable sequence and the pilot has to aim the aircraft at whichever target is lighted. Two flight-test programs were used to assess the suitability of ATLAS. The first program used the United States Air Force (USAF) NT-33A variability stability aircraft to establish that ATLAS provided a task suitable for use in flying qualities research. A head-up display (HUD) tracking task was used for comparison. The second program used the X-29A forward-swept wing aircraft to demonstrate that the ATLAS task was suitable for assessing the flying qualities of a specific experimental aircraft. In this program, the ground attack task was used for comparison. All pilots who used ATLAS found it to be highly satisfactory and thought it to be superior to the other tasks used in flying qualities evaluations. They have recommended that it become a standard for flying qualities evaluations.

- (5) Raabe, K.-H., "TOTDGL, Ein Programm zur Lösung linearer Totzeitdifferentialgleichungssysteme 1. Ordnung," DFVLR-IB 111-88/21 (1988), 73 Seiten, 14 Bilder, 4 Tab. und 7 Lit.

Aircraft and pilot-aircraft systems under investigation are becoming even more complex, especially those containing time delays.

Using conventional integration procedures, these time delays must be approximated by filters in the form of differential equations. This can lead to inaccurate time response representations caused by filter-induced transients. Additionally, the filters increase the order of the system, and the physical meaning of the model is often lost.

To circumvent these problems, a fourth-order Runge-Kutta procedure has been modified to obtain exact solutions of the time-domain flying qualities. The procedure integrates first-order linear differential equations with up to four time delays. The differential equations are fed directly into the computer, so that the time delays do not have to be approximated by filters. The order of the original differential equations is maintained, and the physical meaning survives.

This report provides the mathematical basis for this procedure. The program is illustrated with several detailed examples.

- (6) Wulff, G., Marchand, M., "Interactive Analysis of Flight Test Data," DFVLR-IB 111-88/52 (1988).

Analysis of large time series or complex mathematical models should conveniently be done by the experienced scientist/engineer himself in dialogue mode with the computer. Program systems for data analysis must be easy to handle and must give quick and informative graphical results. Under these aspects and tailored for the special needs of the DLR Institute for Flight Mechanics, some software for the analysis of flight test data and for the determination of handling qualities characteristics has been developed.

The program package DIVA for interactive data analysis consists of a number of modules for generation, preparation, and analysis of time-dependent and frequency-dependent data. It runs under the operating systems MVS and VM of the host computer IBM 4381, using high resolution graphical work stations.

The report gives a detailed description of the different options, which can be selected by the user, including graphical presentations of the input panels and the output plots and listings. Examples are given for the evaluation of flight test data, the analysis of differential equation and transfer function models, the approximation of Low Order Equivalent Models, and the direct application of handling qualities criteria.

- (7) Sridhar, J.K., Wulff, G., "Studies on some Aspects of BO-105 and ATTAS Flight Test Data with MISO Analysis Procedures," DFVLR-IB 111-87/51 (1987).

Multiple input/output (MIMO) analysis procedures for linear systems are known in theory, but very little is known in their applications to flight test data. In practical situations, the flight records are generally correlated, and it is necessary to identify the spectral nature of multiple inputs and to evaluate their separate and combined effects on any desired response records. Use of ordinary coherence functions in these applications will give erroneous results and incorrect interpretation of input/output relations. Dodds and Robson have introduced the concept of partial coherence functions, which in conjunction with ordinary coherence functions sheds tremendous physical insight into the interpretation of coupled spectral nature of stationary random processes.

Recently, Bendat has described computationally efficient iterative procedures by involving a process known as "conditioning" to separate out the linear coupling effects and shown how quantities of interest such as partial and multiple coherence functions, coherent output spectral results for given conditioned inputs, single and multiple frequency response functions and unknown noise spectra, provide greater engineering insight into the physical meaning of various relationships.

In the present paper these techniques have been adopted to develop a general computer program and to study them as engineering tools in aerospace applications. The results are presented by considering flight test data from the two important research flying vehicles ATTAS (Advanced Technologies Testing Aircraft System) and Helicopter BO-105 of DLR.

- (8) Wilhelm, K., Marchand, M., "Low Order Equivalent System Approximation for Longitudinal Motion," AGARD-FMP Working Group 17, Handling Qualities of Unstable Highly Augmented Aircraft, 13-15 April 1988, Warton, UK.

In modern aircraft complex flight control systems and/or unusual vehicle response modes are utilized leading to high order system (HOS) dynamics of these vehicles. To render judgement on the flying qualities of these vehicles, methods have to be provided to describe these HOS dynamics in terms correlatable to the MIL-F-8785 specification. Low order equivalent systems (LOS) appear to be suitable for specifying the flying qualities of highly augmented aircraft systems and have been recommended for assessing MIL-F-8785 specification compliance. The paper deals with the determination of LOS and practical application aspects.

- (9) Hanke, D., Wilhelm, K., Meyer, H.-L., "Development and Application of In-Flight Simulator Aircraft for Flying Qualities Research at DFVLR," NAECON '86 Symposium on Developing Technologies for Revolutionary Application, Dayton, Ohio, 19-23 May 1986, Paper No. 117.

In-flight simulations as a general research technique have been applied by DFVLR since the early 1970s using the HFB 320 aircraft. The HFB 320 is a modified business jet with 5-DOF simulation capability and a simplex digital fly-by-wire system. This in-flight simulator was successfully used in various handling qualities flight experiments until 1984. Based on the experiences gained with the HFB 320, a new advanced in-flight simulator aircraft ATTAS (Advanced Technologies Testing Aircraft System) has been developed recently by DFVLR which will be operational in 1986.

- (10) Hanke, D., Lange, H.-H., "Flight Evaluation of the ATTAS Digital Fly-By-Wire/Light Flight Control System," ICAS-Congress 88-3.6.1, Jerusalem, 28 August - 2 September 1988.

An overview of recent development and flight test experiences of the DLR's flight test vehicle ATTAS equipped with a digital fly-by-wire/light flight control system is presented. System design, multiprocessor communication management, parallel data processing, redundancy management as well as software development and validation are summarized.

Further, the role of ground-based system simulation for development and testing, flight test procedures and some interesting flight test results are dealt with.

- (11) Hanke, D., "Data Processing Concept for the DFVLR Research Aircraft ATTAS," Proceedings of the Third European ROLM Users Group Conference, Braunschweig, 7-9 May 1985.

ATTAS is equipped with a comprehensive on-board computer system, computer controlled control surfaces, modern avionics and interfaces (ARINC 429, MIL-BUS 1553B), changeable flight displays, pilot's controls (ministick) and on-board data acquisition and recording system.

The on-board computer-system is built as a complete duplex system consisting of two independent lanes of each four ROLM MSE/14 and one Hawk/32 computers linked by the SMCA fibre optic bus. Discussed are some aspects of the design guidelines, system integration and ground-based configuration for software development and testing. Further, an overview of the project status is given.

- (12) Lange, H.-H., "Software Development under AOS/VS for ARTS Target Systems," Third European ROLM Users Group Conference, Braunschweig, 7-9 May 1985.

For the DLR ATTAS project software development capability is required of about 20 man/years in the first phase for the on-board ROLM system. Ground-based facilities for software development and simulation had been built up. Strategies for software development are presented, giving an overview of connections between ROLM and DG hardware and software in use.

Experiences with system tools are discussed which give assistance to handle application software to meet requirements for software in an operational airborne system.

- (13) Kevenoglu, M.F., Klewe, H.-J., "Testing-Facilities and -Procedure of the ATTAS On-Board Data Acquisition System," Proc. ETC Telemetry Conference, Aix en Provence/France, 23-25 June 1987, pp. 389-402.

A versatile, highly accurate and testable data acquisition system for the new DLR research aircraft ATTAS has been developed. The system consists of Signal Conditioning (SC)-units and is controlled by a Signal Conditioning Master Controller (SCMC) with integrated PCM-Encoder. It processes software-controlled parameters and adaptable signal inputs.

A subsystem of the ample ATTAS-data acquisition system is constituted by the sensors and the signal conditioning system with "Built In Test Equipment BITE." Additionally the "Test And Calibration System TACS" consisting of controller and measurement equipment is integrated.

The ATTAS measurement system consisting of TACS and Signal-Conditioning SC with BITE permits very fast computer-controlled functional checks of the signal-conditioning system and related sensors in application as a Pre-Flight-Test PFT.

- (14) Jategaonkar, R., Plaetschke, E., "Estimation of Aircraft Parameters Using Filter Error Methods and Extended Kalman Filter," DFVLR-FB 88-15, 1988, 56 pages, 8 figs., 5 tabs., 32 refs.

A comparison of four algorithms for parameter estimation in linear and nonlinear systems accounting for both process and measurement noise using two different approaches, namely direct approach and filtering approach, has been made. In the direct approach the iterative Gauss-Newton method incorporating a suitable state estimator is used to estimate the unknown parameters by optimization of the likelihood function. For the state estimation both time-varying and steady-state filters are used. In the filtering approach the unknown parameters are estimated as augmented states using the extended Kalman filter. The estimation results from three model postulates, one linear and two nonlinear, to extract aircraft derivatives from simulated as well as flight test data, are used for the purpose of comparison. Different aspects, such as convergence, computational time, parameter estimates, and their accuracies are evaluated for each of the four estimation algorithms. A general set of conclusions has been drawn.

- (15) Jategaonkar, R., Plaetschke, E., "Maximum Likelihood Estimation of Parameters in Linear Systems with Process and Measurement Noise," DFVLR-FB 87-20, 1987, 48 pages, 10 figs., 3 tabs., 22 refs.

A FORTRAN program to estimate flight mechanical parameters in linear systems has been developed. The maximum likelihood method which accounts for both process and measurement noise has been used for this purpose. The algorithm is based on a Kalman filter for the linear state estimation problem, an explicit estimation of covariance of residuals, and the modified Newton-Raphson method for parameter update. Several computational options have been incorporated which enable convenient application in different practical situations. Utility of the algorithm has been demonstrated on a number of examples.

- (16) Jategaonkar, R., Plaetschke, E., "Identification of Moderately Nonlinear Flight Mechanics Systems with Additive Process and Measurement Noise," AIAA Atmospheric Flight Mechanics Conference, 15-17 August 1988, Minneapolis, Minnesota.

The parameter estimation problem for dynamic systems with both process and measurement noise from nonlinear model postulates is addressed in this paper. A two step estimation procedure computes explicitly the covariance matrix of residuals and updates the system parameters, the initial conditions, as well as the state noise matrix using the Gauss-Newton optimization method. For the purpose of state estimation in nonlinear systems with process noise, an approximate steady-state filter is used. In each iteration the filter-gain matrix is obtained from the postulated system model linearized at the updated initial conditions. The gradients of the output variables and of the system functions are approximated by finite differences. The

proposed approach for nonlinear systems with unknown process and measurement noise covariances is first validated on simulated aircraft response data. It is then applied to estimate from flight test data the aircraft longitudinal derivatives using two models with different degrees of nonlinearities. Advantages and possible limitations of the method are discussed.

- (17) Jategaonkar, R., Plaetschke, E., "Maximum Likelihood Estimation of Parameters in Nonlinear Flight Mechanics Systems," IFAC Identification and System Parameter Estimation, York, UK, 1985.

Two methods for maximum likelihood estimation of flight mechanics parameters have been developed. They are applicable to system models which may be nonlinear in the state and control variables as well as in the parameters to be estimated. The optimization problem has been solved by using both minimum search methods and quasi-linearization method. Advantages and disadvantages of both methods are discussed. In the latter case the need for deriving explicit sensitivity equations have been overcome by approximating the sensitivity coefficients by numerical differences. This results in a computationally attractive implementation of the estimation method for routine applications to general nonlinear systems. These techniques have been applied to the problems of kinematic consistency checking of flight test data as well as estimation of aerodynamic derivatives.

- (18) Plaetschke, E., "Identification of Unstable Flight Mechanics Systems by Using an Output Error Method," Z. Flugwiss. Weltraumforsch. 12 (1988) 233-240.

The identification of unstable systems using an output error method leads to severe numerical difficulties. If the starting values of the system parameters to be estimated are not close enough to the exact values, the integrated solutions may diverge and possibly exceed the value range of the computer (overflow). These problems can be eliminated when the output error method is stabilized by a feedback of the output errors to the state variables. The modified method was tested on simulated data of an unstable aircraft and was successfully applied to the identification of the US research aircraft XV-15.

- (19) Rohlf, D., Mönnich, W., "Identification of the DLC-Flap System of the Research Aircraft ATTAS," Flight Testing World Wide, of Flight Test Engineers, Amsterdam, 28 September - 2 October 1987, 18th Annual Symposium Proceedings, Paper 12.

This paper deals with a nonlinear system identification problem with emphasis on the following two items of interest:

- 1) the nonlinear modelling of the dynamic behaviour of a DLC-flap actuator system and the estimation of its characteristic parameters and
- 2) the determination of the aerodynamic DLC-flap efficiency including lift, drag and moment.

In respect of item (1) a simplified equivalent model for the actuator system has been proposed in two phases considering a linear system in the frequency domain and a nonlinear system in the time domain. The maximum likelihood method has been used in both the cases for system identification. The same method has been further used for system identification in respect of item (2) in time domain only. The nonlinear modelling of the aerodynamic DLC-flap efficiency is considered here. The paper presents the mathematical modelling and the results of the identification.

- (20) Henschel, F., Chetty, S., "Model Following Flight Control System Design for ATTAS, DFVLR's New In-Flight Simulator," AIAA Guidance, Control, and Navigation, J. of Aircraft (1988).

The content of this paper describes the theoretical development and nonlinear digital simulation results of the model following flight control system for a new in-flight simulator. A detailed description of the manner in which the feedforward and feedback gains are obtained using an interactive computer aided design technique is given. Additional filters in the forward loop enable the feedforward gains to be made independent of the model aircraft parameters even when the actuator dynamics are explicitly modelled. The feedback gains are obtained by using a vector optimization technique. Several time and frequency domain measures are used to obtain the required performance. Modified robustness measures based on singular value decomposition are used to constrain the feedback gains. The sensitivity of the model following system to changes in flight condition is minimized using a multi model formulation. Nonlinear simulation results are presented to show the quality of the model following to substantiate the theory and design procedure.

- (21) Henschel, F., "On Control Concepts for In-Flight Simulation Including Nonlinearities and Time-Delays," DFVLR-FB 85-24, 1985, and ESA TT-948, 1985.

The structure of the complete model-following system is divided into two parts. The first one consists of feedforward branches. If a linear description of the model and the basic aircraft is assumed an exact model-following is achieved by this part. For the control matrices algebraic expressions are derived. In those equations the influence of actuator dynamics is considered. In addition a set of formulas is developed in which all variables are assumed to be discretized for processing on a digital computer. By the second subsystem an error suppression is achieved. The application of a cost vector method is demonstrated for one example. It is shown that also nonlinearities and time lags can be included in the calculations of the feedback gains.

- (22) Henschel, F., Bouwer, G., "Design of Higher Bandwidth Model Following for Flight Vehicle Stabilization and Control," 16th ICAS Congress, Jerusalem, 1988.

The paper describes the general design of a Model Following Control System (FMCS), which is accomplished in several sequential steps. To start with, a suitable

structure for the controller is chosen depending on the physical properties of the system and operating constraints. The feedforward gains are determined by calculating a pseudo inverse of the control input matrix assuming the plant to be linear. The feedback gains are obtained by using an interactive vector performance optimization technique. The desired design goals are achieved by selecting a proper set of performance criteria in the time and frequency domain. The design obtained by this procedure is tested extensively using offline and ground-based nonlinear and real-time simulation facilities.

The approach is applied both to the fixed wing and helicopter in-flight simulators ATTAS (VFW 614) and ATTHes (BO 105) at DLR. Simulation results demonstrate the effectiveness of the MFCS in obtaining good model matching and desired disturbance rejection with good crossover properties.

- (23) Hanke, D., Bauschat, J.-M., Lange, H.-H., Heutger, H., "In-Flight Simulator ATTAS - System Design and Capabilities," International Symposium "In-Flight Simulation for the 90's," Braunschweig, 1-3 July 1991, Conference Proceedings DGLR-91-05.

The In-Flight Simulator ATTAS is a general purpose testbed for flying qualities and flight control research at DLR, Braunschweig. This paper describes the system design elements and main modifications of the VFW 614 based aircraft. Main emphasis is laid on the digital fly-by-wire/light flight control and the in-flight simulation system, their functions, and the simulation envelope. ATTAS provides six-degree of freedom model representation by using linear or nonlinear equations of motion. Recent advances in improving the simulation fidelity by using quasi-nonlinear feedforward loops will be demonstrated by flight test results. Further, simulation performance and in-flight simulation fidelity criteria will be discussed.

APPENDIX B: ABSTRACTS OF WL TECHNICAL DOCUMENTS

(1) Flying Qualities of Piloted Vehicles, MIL-STD-1797 (USAF), 31 March 1987

This Military Standard gives a framework for tailoring flying qualities requirements to any particular procurement, and the accompanying handbook provides material and guidance for this tailoring. The requirements are organized by axis of control. For each requirement the handbook gives a rationale. Guidance includes (a) recommended detailed requirements for various applications, (b) supporting data, (c) indicators of critical flight conditions, and (d) verification techniques. Many lessons learned are included.

(2) DiDomenico, E.D., Biezas, D.J., "Loop Separation Parameter for Landing Flying Qualities," AIAA, 1984.

Control Anticipation Parameter (CAP), used in MIL-F-8785C as a longitudinal handling qualities criterion, does not distinguish between different phases of terminal-area flight. The crossover pilot model is combined with classical root locus and frequency response method to establish a frequency separation criterion called Loop Separation Parameter (LSP) for longitudinal evaluation during landing. LSP provides an acceptable prediction of pilot rating (Cooper-Harper scale) for the landing phase, and when applied to flight test data (LAHOS) indicates a transition in pilot emphasis from pitch attitude control to flight path angle control in the landing flare. Recent developments in multi-channel time series modeling are applied to further substantiate the results.

(3) Anderson, M.R., Schmidt, D.K., "Closed-Loop, Pilot/Vehicle Analysis of the Approach and Landing Task," AIAA Journal of Guidance, Control, and Dynamics 10 (1987) 2, p. 187.

Fundamental to optimal-control-theoretic modeling and frequency-domain analysis of manually controlled dynamic systems is the interplay between pilot workload and closed-loop pilot/vehicle performance and stability robustness, which can be measured by the required pilot phase compensation. When applied to the flight-test data for 32 highly-augmented fighter configurations in the approach and landing task, strong correlation was obtained between the analytical and experimental results.

(4) Boettcher, K., et al., "On Deciding Display Dynamics Requirements for Flying Qualities," Proc. IEEE National Aerospace and Electronics Conference, NAECON 88, p. 480, May 1988.

An approach for deciding display dynamics requirements for flying qualities is based on multivariable control analysis, using the optimal control model to represent nominal pilot behavior. Given an uncertainty structure for the nominal model that reflects

likely pilot variabilities, structured singular value techniques are used to examine and determine display dynamics that strike a balance between the goals of optimal system performance and tolerance to pilot variability. The approach is illustrated by an example which supports its potential utility.

- (5) McCormack, L.B., George, F.L., "Impact of Display Dynamics on Flying Qualities," Proc. IEEE National Aerospace and Electronics Conference, NAECON 86, May 1986.

This paper describes an analysis and experiment performed by the Flight Dynamics Laboratory using a pursuit display to investigate the effects of varying display time delay, bandwidth and damping as well as the impact of degraded aircraft response on pilot workload and performance.

- (6) McCormack, L.B., et al., "Improving Pilot-Vehicle Integration Using Cockpit Display Dynamics," Proc. IEEE National Aerospace and Electronics Conference, NAECON 87, p. 530, May 1987.

Display dynamics were evaluated in a simple pitch pursuit tracking task by nine pilots in a fixed-base simulator. Rms tracking errors were found to increase as display delay increased. Delays on the order of 0.150 sec or more resulted in increases in rms errors which may prevent satisfactory mission completion. Higher display damping ratios improved performance at lower bandwidths but took on less importance as bandwidth increased.

- (7) Pujara, L.R., "Computer-Aided Control Systems Design Technique with Applications to Aircraft Flying Qualities," AIAA J. Guidance, Control, and Dynamics 11 (1988) 3, p. 250.

This paper proposes a frequency-matching technique for the design of single-input, single-output control systems. The parameters of a cascade controller are determined by minimizing a weighted mean square error between the frequency responses of the compensated closed-loop system and a desired closed-loop system. The error is so defined that the controller parameters turn out to be solutions of linear algebraic equations. The method is applied to design of a pitch control system meeting short-period frequency and damping requirements.

- (8) Gentry, T.A., Pujara, L.R., "An Example of Preliminary Longitudinal Flying Qualities Design Using a Frequency Matching Method," Proc. IEEE National Aerospace and Electronics Conference, NAECON 85, p. 647, May 1985.

Pujara's program was used for a first cut at design of pitch control laws for an unstable airframe to meet MIL-F-8785C short-period frequency and damping requirements.

- (9) Pujara, L.R., "A Note on the Parameterization of Stabilizing Controllers for SISO Systems," AIAA Paper 88-4082-CP, August 1988.

A simple, useful procedure solves the Bezout identity in the domain of stable rational transfer functions for finding the parameterization of all stabilizing controllers for single-input, single-output control systems. Solution of linear simultaneous equations leads to a relatively lower order for the controller and the compensated closed-loop transfer functions. The procedure is illustrated by designing the longitudinal-model control systems for the YF-16 aircraft having satisfactory flying qualities.

- (10) Hoh, R.L., Mitchell, D.G., "Tentative STOL Flying Qualities Criteria for MIL Standard and Handbook," AFWAL-TR-83-3059, June 1983.

This report is the result of review, analysis, and unification of existing STOL flying qualities data in a form facilitating inclusion into the new MIL Standard and Handbook, particularly in the area where STOL aircraft differ from CTOL aircraft. Requirements are proposed where sufficient data exist, and where data are sparse or nonexistent a discussion is presented.

- (11) Hoh, R.L., Mitchell, D.G., "STOL Handling Qualities Criteria for Precision Landings," AFWAL-TR-86-3050, November 1986.

The proposed criteria have two elements: (1) the proper response-type for the task and (2) the minimum attitude and flight-path bandwidths. Supporting data are reasonably complete for powered-lift STOLs, but less so for fighter STOLs, which use precise touchdown and thrust reversing to achieve short landings. A brief piloted moving-base simulation on the USAF LAMARS was supplemented by data available from an in-flight simulation of precision landings.

- (12) Suchomel, C.F., "Nonlinear Flying Qualities - One Approach," AIAA-87-0347, January 1987.

This paper describes the need for nonlinear flying quality metrics, followed by a discussion of the use of a truncated nonlinear Volterra series to solve the system of aircraft acceleration equations to obtain the system velocities. Numerical results illustrate the accuracy of this approach. The paper concludes with a description of how the Volterra series can be used to define nonlinear flying quality metrics analytically.

- (13) Baumann, W.T., et al., "Recent Work Using Volterra Series as a Methodology to Analyze Nonlinear Aircraft Dynamic Properties," Sixth Annual Conference on Mathematical Modeling, 4-7 August 1987, St. Louis, MO.

Preliminary results are discussed which demonstrate the accuracy of the Volterra series approach and its potential for defining nonlinear flying quality parameters. Simulations are presented which show that two-term Volterra submodels predict nonlinear responses, such as limit cycles, that are not predicted using piecewise linear techniques. Incorporating higher-order terms in the approximation is shown to result in more accurate predictions.

- (14) Morton, B.G., et al., "Nonlinear Flying Quality Parameters Based on Dynamic Inversion," AFWAL-TR-87-3079, October 1987.

Tools were developed that can be used for the computation of nonlinear flying quality parameters. A variety of candidate nonlinear flying quality parameters and candidate specifications for them were developed. These parameters are genuinely different from expressions derived from linearized models. They depend on the nonlinear aerodynamic functions themselves and not their derivatives, and these parameters can be computed directly from preliminary nonlinear aircraft models.

- (15) Myers, T.T., et al., "Flying Qualities in Nonlinear Large Amplitude Maneuvers," AIAA/AHS/ASSEE Aircraft Design, Systems, and Operations Meeting, 14-16 September 1987.

Flying qualities may be aircraft-centered (e.g., control power), task-centered (e.g., agility) or pilot-centered (e.g., control harmony, coordination). Trajectory equations were developed by means of differential geometry, and related to inertial and aircraft body axes. The concept is illustrated by example maneuvers. Inverse solution techniques for aircraft and control variables were developed. Perturbations from accelerated equilibria were then considered. Finally, quasilinear and even-function approaches to nonlinear flight mechanics problems are discussed. The literature on fighter tactics/maneuvers was surveyed. (A detailed final report will be releasable in March 1989.)

- (16) Sturmer, S.R., "Pitch Rate Sensitivity Criterion for Category C Flight Phases - Class IV Aircraft," AIAA 86-2201, August 1986.

Since the high-frequency gain of the transfer function is important to the man-in-the-loop system stability and performance, a flying qualities criterion for the selection of this gain is necessary. The criterion proposed uses the aircraft's pitch rate frequency-response to plot amplitude ratios versus phase angles. The available data indicate that the desired pitch rate sensitivity for a range of response dynamics results in a relatively constant amplitude-phase plot.

- (17) Hoh, R.H., Mitchell, D.G., Sturmer, S.R., "Handling Qualities Criteria for STOL Landings," IEEE National Aerospace and Electronics Conference, NAECON 87, May 1987.

This paper reports on a research effort to expand the proposed handling qualities MIL-Standard and Handbook to include criteria for STOL aircraft. The primary focus has been on non-powered-lift aircraft capable of using good portions of bomb-damaged runways. The criteria must account for both pitch attitude and flight path control, and must specify the applicable short-term response-type.

- (18) Joshi, D.S., et al., "Expert-Aided Approach to the Usage of Handling Qualities Specification," 1986 NAECON Conference, May 1986.

An expert-aided approach has been developed for the usage of "Flying Qualities of Piloted Airplanes," specification MIL-F-8785C. The prototype system consists of three rule bases: a "Matching Rule Base," a "Requirements Rule Base" and "Control Synthesis Rule Base." The technique is illustrated through a flight control system design example.

- (19) Koehler, R., et al., "GRATE - A New Flight Test Tool for Flying Qualities Evaluations," AGARD Flight Mechanics Panel Meeting on Flight Test Techniques, Edwards AFB, Ca., USA, October 1988.

GRATE is a DLR flight test tool in which sequentially lit lights in an array on the ground serve as targets for an air-to-ground simulated gunnery run. A like array, incorporated into a terrain board, was evaluated with the AFWAL LAMARS moving-base simulator by two pilots, one of whom had flown against GRATE in Germany. The simulation verified that the technique is an effective tool for unmasking aircraft handling problems. The effects of turbulence on pilot ratings were found to be small in comparison to conventional methods.

- (20) Baumann, W. T., et al., "A Volterra Series Submodel Approach to Modelling Nonlinear Aerodynamics Systems," May 1988.

High performance aircraft have mission requirements for operating in high angle-of-attack and sideslip conditions and in various maneuvers of unsteady, large amplitudes governed by multiple-input, multiple-output nonlinear dynamics. The large amplitudes coupled with high-degree nonlinear dynamics lead to requirements for nonlinear flying qualities. These qualities require analyses of nonlinear dynamic stability, nonlinear control, and nonlinear response behavior of such aircraft. Techniques are needed that (1) are computationally feasible, (2) retain the nonlinearities of the aircraft, and (3) provide physical and mathematical understanding of the important nonlinear flying qualities. This report documents the results of efforts to develop such techniques using the Volterra Series representation for nonlinear aircraft models of high- α flight.

- (21) Mitchell, D.G., et al., "Minimum Flying Qualities," WRDC-TR-89-3125, January 1990.

The project was initiated to explore the modern nature of minimum flying qualities in the presence of modern aircraft and multiredundant flight control system technology. It had several phases, including 1) an intensive effort to develop and/or elaborate existing pilot modeling analysis techniques to apply to situations associated with minimum flying qualities, divided attention pilot operations, and multiaxis control tasks; 2) preliminary analyses and associated fixed-base simulations to expand the meager multiaxis data base and to serve as pilot studies for more extensive simulations on the Air Force's Large Amplitude Multimode Aerospace Research Simulator; 3) an extensive simulation program on LAMARS to investigate minimum flying qualities and related situations; and 4) analysis and interpretation of both the early and LAMARS simulation efforts in the context of the pilot modeling advances.